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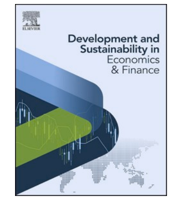

Exploring the nexus of economic growth, energy mix, services, trade openness, and environmental quality: Evidence from N11 countries

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A R T I C L E I N F O

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A B S T R A C T

Despite considerable research on the connections between economic growth, energy consumption, trade, and environmental sustainability, a notable gap persists in understanding the varying effects of these factors at different levels of resource use. This study seeks to fill this gap by utilizing quantile panel regression analysis to investigate the intricate interactions among these variables in the N11 countries. Our results indicate that economic growth has a negative impact on environmental sustainability, particularly at higher levels of resource consumption. In contrast, the consumption of renewable energy has a positive effect on sustainability, whereas reliance on non-renewable energy and trade openness produces adverse outcomes. These findings highlight the urgent need for policymakers to pursue a balanced approach to economic development that emphasizes environmental sustainability and considers the social implications of the transition.

1. Introduction

This paper explores the complex relationship between economic growth, energy mix, services, trade openness, and environmental quality, particularly within the N11 countries. By focusing on this nexus, we seek to shed light on how economic activities, energy consumption patterns, and trade policies influence environmental sustainability, providing crucial insights for sustainable development strategies.

The topic at hand encompasses interconnected themes central to sustainable development and environmental stewardship. Economic growth, often viewed as a driver of prosperity, is scrutinized for its environmental ramifications, particularly in energy utilization and trade dynamics. This study delves into the nuances of these relationships, examining how different energy mixes, varying levels of trade openness, and the provision of services contribute to or mitigate environmental impacts. By untangling these complexities, we aim to contribute to a deeper understanding of how economic activities can align with environmental goals.

The ecological footprint serves as a comprehensive economic-ecological indicator for assessing environmental sustainability, as it captures human-induced impacts on air, water, and soil. This accounting system includes two key components: the "demand-side" (ecological footprint) and the "supply-side" (biocapacity). The ecological footprint quantifies the demand for natural resources in global hectares, while biocapacity measures nature's ability to supply these resources in the same units. Industrialization diminishes biocapacity and heightens the ecological footprint, exerting adverse effects on the load capacity factor and leading to environmental degradation. The load capacity factor, which compares biocapacity with the ecological footprint, helps monitor ecological thresholds and provides insight into environmental health. As the load capacity factor decreases, environmental degradation tends to increase.

Studying the relationship between economic growth, energy mix, services, trade openness, and environmental quality is crucial. As global concerns about climate change, resource depletion, and environmental degradation mount, there is a growing recognition of the need for sustainable development pathways. Insights from this research are pivotal for policymakers, businesses, and civil society actors as they navigate the complexities of balancing economic development with environmental preservation. By elucidating the impacts and trade-offs associated with different policy choices and economic strategies, this study aims to provide actionable knowledge for informed decision-making.

The N11 countries, also known as the Next Eleven, refer to a group of eleven emerging economies identified by Goldman Sachs in 2005 as having the potential to become major players in the global economy in the 21st century. These countries are: Bangladesh, Egypt, Indonesia, Iran, Mexico, Nigeria, Pakistan, Philippines, South Korea, Turkey, and Vietnam. They are characterized by rapid population growth, urbanization, industrialization, and a growing middle class. While all are expected to experience significant economic growth, it may not be at the

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same pace as the original BRIC economies (Brazil, Russia, India, and China).

The N11 countries, which include a wide range of economies from Nigeria to Indonesia and from Bangladesh to Mexico, constitute a substantial portion of the global economy. These nations share common traits such as rapid population growth, urbanization, industrialization, and an expanding middle class. However, they also encounter unique challenges related to environmental sustainability, resource management, and social equity. This research highlights the significance of context-specific analyses and underscores the necessity for customized solutions to address the sustainability challenges specific to these economies.

Our analysis employs annual data spanning from 1995 to 2021 for 11 N11 countries, concentrating on variables including the load capacity factor, non-renewable energy consumption, renewable energy consumption, value-added from services, GDP per capita, and trade openness. We apply panel unit root tests, cointegration tests, and quantile panel regression to investigate the long-term relationships and varying effects across different quantiles of the load capacity factor.

This research makes important contributions to the existing body of literature by offering several new perspectives. First, unlike prior studies that have predominantly concentrated on the overall effects of economic growth, energy use, and trade on environmental sustainability, our analysis explores the varying impacts across different quantiles of the load capacity factor. This approach enables us to pinpoint how these variables affect environmental outcomes at varying degrees of resource utilization and environmental stress. Second, we introduce the service sector into our investigation, acknowledging its increasing role in modern economies and its potential influence on environmental sustainability. By analyzing the interaction between economic growth, energy composition, services, and trade within the framework of the N11 countries, our research delivers a more detailed and refined perspective on the elements driving environmental sustainability.

This research extends beyond theoretical insights to practical implications for policy and practice. By utilizing rigorous empirical methods and advanced econometric techniques, we reveal nuanced relationships and causal links that enhance our understanding of sustainability dynamics. Our findings emphasize the diverse impacts of economic growth, energy choices, and trade policies on environmental quality, highlighting the necessity for integrated approaches to sustainable development. The evidence presented in this paper provides valuable insights for policymakers and stakeholders aiming to promote economic prosperity while preserving environmental integrity in the N11 countries and beyond.

For sustainable development, policymakers should focus on investing in renewable energy sources and encouraging sustainable consumption practices. This strategy will help alleviate the adverse environmental effects of economic growth and energy use. Moreover, it is crucial to adopt a balanced approach that takes into account both environmental sustainability and social equity to ensure a fair and just transition to a greener future.

After this introductory section, the subsequent part outlines the literature review, methodology employed and describes the data used. Section 4 illustrates the empirical findings of the analysis, Section 5 illustrates the discussion, while Section 6 wraps up with suggested policy recommendations.

2. Literature review

Understanding the complex interplay between economic activities, energy consumption, and environmental sustainability is essential for informing policy interventions aimed at mitigating climate change and promoting sustainable development. The results of empirical studies examining the dynamics of CO2 emissions, load capacity factor (LCF), ecological footprint (EF), and the impact of services added value (AVS) on environmental outcomes across various countries are summarized in Table 1. Several studies have delved into the relationship between CO2 emissions and economic variables within N11 countries and comparable regions.

Aydoğan and Vardar (2020) utilized Pedroni's (1999; 2004) and Kao's (1999) residual cointegration tests, OLS, FMOLS, DOLS, and panel causality tests to reveal a positive association between CO2 emissions and real GDP, non-renewable energy consumption, and agricultural value added (AVA) across E7 countries from 1990 to 2014. Conversely, they found a negative relationship between CO2 emissions and the square of real GDP and renewable energy consumption (REC). (Tuan et al.,) examined the optimization of renewable energy sources operation in Vietnam's electricity market. Similarly, Liu et al. (2017) focused on ASEAN-4 countries from 1970 to 2013, utilizing Pedroni's and Kao's tests, OLS, FMOLS, DOLS, and panel causality tests. The results revealed that renewable energy negatively impacts carbon dioxide emissions, whereas non-renewable energy positively affects them. Additionally, the study found that agricultural value added negatively impacts CO2 emissions, with unidirectional linkages identified from agriculture and real GDP to emissions.

The load capacity factor (LCF) serves as a broad indicator of environmental sustainability, reflecting the balance between a region's ecological footprint (EF) and its biocapacity. The EF represents the demand for natural resources, while biocapacity indicates the environment's ability to replenish those resources. A high LCF suggests that a region is operating within its ecological limits, whereas a low LCF signals that it is overusing resources and surpassing its biocapacity, leading to unsustainable depletion. We selected LCF as the main measure of environmental sustainability because it offers a comprehensive evaluation of human impacts on the environment, accounting for both resource use and ecological renewal. This integrative perspective enables us to better capture the complex relationships between economic activities, energy consumption, and environmental quality.

Research on ecological footprint (EF) across various Asian, South Asian, and European countries has uncovered significant insights into the impacts of economic growth, trade openness, and energy consumption on environmental footprints. Lu (2020) examined 13 Asian countries from 1973 to 2014, utilizing PMG and causality tests, and identified a positive impact of economic growth (EG) and energy consumption (EC) on EF. On the other hand, Sabir and Gorus (2019) focused on South Asian countries from 1975 to 2017 using ARDL models, revealing that trade openness, foreign direct investment (FDI), and the KOF index positively affect the ecological footprint.

Studies investigating load capacity factor (LCF) have provided valuable insights into its dynamics concerning economic variables and energy-related factors. Pata and Isik (2021) analyzed LCF in China from 1981 to 2017 using dynamic ARDL models, highlighting the impacts of gross domestic product (GDP), energy intensity (EI), and non-renewable resources (NRR) on LCF. Similarly, studies by Pata and Samour (2022), Alola et al. (2023), and others have explored LCF dynamics in different countries and regions, showcasing various factors influencing LCF such as GDP, energy consumption, and renewable resources.

The relationship between services added value (AVS) and environmental factors has been a subject of extensive study, particularly in OPEC countries and European regions. Murshed et al. (2020) investigated CO2 emissions in 12 OPEC countries from 1992 to 2015, utilizing dynamic SDM models, and found that energy consumption, urbanization, and economic sectors have significant impacts on emissions. Similarly, Ramos et al. (2018) focused on Portugal from 1996 to 2013, employing OLS methods, and discovered significant positive associations between CO2 emissions and various sectors of economic activity. Elish (2022b) conclude that governments should foster their productive capabilities and ensure political stability to maintain a favourable investment climate that encourages firms to grow their overseas investments.

The existing literature provides valuable insights into the relationship between economic activities, energy consumption, and load

Table 1
Summary of the literature, with reference to their region, methodology and key findings.

Authors	Countries/regions	Period	Variables	Methods	Findings
1. **N11 Countries and CO2**					
Aydoğan and Vardar (2020)	E7 (Brazil, China, India, Indonesia, Mexico, Russia and Turkey)	1990–2014	CO2, GDP, AVA, REC, NREC	Pedroni's (2004) and Kao's (1999) residual cointegration tests, OLS, FMOLS, DOLS, Panel causality test	Relationship with CO2 Emissions: Positive:Real GDP, Non-renewable Energy Consumption, Agricultural Value Added Negative: Square of Real GDP, Renewable Energy Consumption
Liu et al. (2017)	ASEAN−4 (Indonesia, Malaysia, the Philippines, and Thailand)	1970–2013	CO2, GDP, AVA, REC, NREC	Pedroni's (2004) andKao's (1999) residual cointegration tests, OLS, FMOLS, DOLS, Panel causality test	Impact on CO2 Emissions: Renewable Energy: Negative Impact; Non-renewable Energy: Positive Impact; Agricultural Value Added: Negative Impact Causalities: Unidirectional linkages found: Agriculture and Real GDP to emissions Short-run causalities exist: Non-renewable energy to agricultural value added; Real GDP to agriculture; Agriculture to renewable energy consumption.
Karkacier et al. (2006)	Turkey	1971–2003	ENUSE, AGRPROD, GROSSADD	Double log-linear model	Determinants of Agricultural Productivity: Energy Use: Important determinant Gross Additions to Fixed Assets: Significant determinant; Relationship with Energy Use: Agricultural productivity increases with energy use
Mushtaq et al. (2007)	Pakistan	1972–2005	OILC,GASC, ELEC,GDP	Johansen cointegration, Granger causality.	Uni-directional Causality: GDP and Oil Consumption; Electricity and GDP Neutrality Hypothesis: Gas and GDP Causal Relationships Found: Agricultural GDP and Oil Consumption; Electricity Consumption and Agricultural GDP
Raihan (2023)	Vietnam	1984 - 2020	CO2,GDP, ENUSE,AVA	ARDL bounds test, VECM, FMOLS, Toda-Yamamoto causality test	Impact on CO2 Emissions: Increase: Economic Growth; Energy Use Reduction: Enhancing Agricultural Added Value
Adebayo et al. (2023)	Pakistan	1965- 2021	CO2, GDP AVA,URBAN, ENUSE	Causality in continuous wavelet transform	Impact on Economic Growth: Positive Impact: Urbanization; Agriculture; Energy Consumption;CO2 Emissions Feedback Causality: between Economic Growth and CO2 Emissions, Urbanization, Energy Consumption, and Agriculture
Ali et al. (2019)	Pakistan	1961–2014	CO2,GDP,AVA, LAND	(ARDL) model and Granger causality test	Long-run Association: Positive and Insignificant Association between CO2, Land Under Cereal Crops, and Agricultural Value-Added. Short-run Association:Negative and Statistically Insignificant Association between CO2 and GDP.
Rehman et al. (2019)	Pakistan	1987–2017	CO2, ENUSE, WATER,FERT	Johansen cointegration, ARDL	Long-Run Positive Association with CO2: Cropped Area; Energy Use; Fertilizer Offtake; Water Availability
2. **Ecological Footprint**					
Lu (2020)	13 Asian countries	1973–2014	EF, GDP, EC, TR	PMG, Causality	Impact on EF: Trade Openness: Not Significant Positive Impact: Economic Growth (EG); Energy Consumption
Sabir and Gorus (2019)	South Asian countries	1975–2017	Ef. FDI, TR KOFi	ARDL	Positive Impact on EF:Trade Openness;Foreign Direct Investment (FDI); KOF Index
Kongbuamai et al. (2020)	Thailand	1974–2016	EF, TR, TOUR, POPDEN	ARDL, VECM Granger causality	Relationships with Ecological Footprint (EF): Positive:Trade Openness; Economic Growth; Energy Consumption Negative: Tourism; Population Density
Alola et al. (2019)	16-EU countries	1997–2014	EF, REC, NREC, GDP, TR, FER	PMG-ARDL	Trade openness decreases the EF
Destek and Sinha (2020)	OECD countries	1980–2014	EF, REC, NREC, GDP, TR	Cointegration, FMOLS, DOLS	Effect on Ecological Footprint (EF): Trade Openness and Renewable Energy: Decrease EF; Economic Growth (EG): U-shaped Association with EF
Elish (2022a)	24 countries	2006–2017	EF, Gender gap	Quantile Panel regressions	gender gap was observed to widen EFP at higher quantiles while narrowing it at lower quantiles
3. **Load Capacity Factor**					
Pata and Isik (2021)	China	1981–2017	LCF, GDP, HC, NRR, EI	Dynamic ARDL	GDP, EI, NRR decrease LCF; HC increase LCF
Pata and Samour (2022)	France	1977–2017	LCF, GDP, REC, NEC	Fourier TY causality; Fourier ARDL	GDP decrease LCF; NEC increase LCF GDP and NEC → LCF
Alola et al. (2023)	India	1965–2018	LCF, GDP, REC, NREE, FD, TO	Pesaran–Shin–Smith cointegration; ARDL	Yes FD and TO decrease LCF; REC and NREE increase LCF
Guloglu et al. (2023)	26 OECD countries	1980–2018	LCF, GDP, REC, HC, NRR, URB	Westerlund cointegration	URB decrease LCF; HC, NRR and REC increase LCF; GDP mixed LCF

(continued on next page)

Table 1 (*continued*)

Authors	Countries/regions	Period	Variables	Methods	Findings
Pata and Balsalobre-Lorente (2022)	Turkey	1965–2017	LCF, Tourism, GDO, EC	Dynamic ARDL	GDP reduces LFC
Shang et al. (2022)	10 ASEAN countries	1980–2018	LCF, GDP, REC, HLT	ARDL	GDP reduces LFC
Fareed et al. (2021)	Indonesia	1965–2014	LCF, GDP, FFEC, EXPODIV,REC	Fourier quantile causality	GDP reduces LFC
Awosusi et al. (2022)	South Africa	1980–2017	GDP, NREN, TEC, GLO, LCF	ARDL	GDP reduces LFC
Agila et al. (2022)	South Korea	1970–2018	LCF, GDP, REC, NREC, TR	Quantile cointegration	GDP reduces LFC
4. Services added Value and Environment					
Murshed et al. (2020)	12 OPEC countries	1992–2015	CO2, EC, URB, GDP. TOUR, AVS	dynamic SDM model	Increase in CO2 Emissions: International Trade; Urbanization; National Income from Construction Sector; Decrease in CO2 Emissions: Energy Consumption; National Income from Tourism Sector; National Income from Transportation Sector (Short Run)
Ramos et al. (2018)	Portugal	1996–2013	CO2, AVA, AVM, AVS, AVTR	OLS	Almost all the sectors of activity present a significant and positive behavior, thus indicating that they contribute to the increase of the level of CO2 emissions.

capacity factor. However, there are notable gaps that need to be addressed. First, while current research offers a solid foundation for understanding the connections between economic activities, energy use, and environmental sustainability, significant gaps remain, particularly within the context of the N11 countries. Additionally, there is a dearth of studies specifically examining how some economic variables in various N11 countries interacts with load capacity factors. Furthermore, comprehensive research on how other economic sectors, such as industry and services, influence load capacity factors across the N11 countries is lacking. By addressing these gaps and incorporating a novel approach that includes the energy mix and service sector into our models, we can gain a better understanding of the factors influencing load capacity factors in the N11 countries. This will provide a more comprehensive understanding of the elements driving load capacity factor and inform evidence-based policy interventions for environmental sustainability in these nations. Our selection of variables is guided by a substantial body of research examining the connections between economic growth, energy consumption, and environmental sustainability. Previous studies have underscored the significance of these elements in analyzing load capacity factors. By integrating these variables into our study, we seek to deliver a thorough and nuanced understanding of the drivers of environmental sustainability in the N11 countries.The reason for using the quantile panel regression needs to be justified by clear hypothesis.

3. Data and methodology

Table 2 provides an overview of variables, their definitions, measurement methods, and data origins. The variables listed are Load capacity factor, Non-renewable energy consumption (quad Btu per capita), Renewable energy consumption (quad Btu per capita), Services value added (% of GDP), Gross domestic product per capita (Constant 2015 US $), and Trade openness (expressed as the ratio of exports plus imports to GDP). The specifics regarding how these variables are measured and where the data comes from are thoroughly explained, primarily drawing from sources such as the World Development Indicators (WDI), the Global Footprint Network (GFN), and the Energy Information Administration (EIA). This documentation serves as a crucial resource for comprehending and analyzing the dataset, thereby facilitating further exploration into various economic and environmental dynamics.

The summary statistics in Table 3 offer a concise overview of key variables. Load Capacity Factor (LCF) averages around 0.52, with a standard deviation of approximately 0.25, indicating moderate variability around the mean. Gross Domestic Product (GDP) per capita, measured in constant 2015 US dollars, has a mean value of 4934.78, with substantial variability as shown by a standard deviation of 5985.96. Trade openness (TO) is relatively high, with an average of 52.76 % of GDP, showcasing an open economic environment. Renewable energy consumption (REN) per capita averages at 0.20, with a notable standard deviation of 0.19, suggesting varying levels of adoption across regions. Non-renewable energy consumption (NREN) per capita stands at an average of 3.29, displaying a higher mean compared to renewable sources. Services value added (AVS) as a percentage of GDP averages around 49.21 %, indicating a significant contribution of

Table 2
Documentation of variables and sources.

Variable	Definition	Measurement	Source
LCF	Load capacity factor	The ratio between the biocapacity and the ecological footprint	GFN
NREN	Non-Renewable energy consumption	(quad Btu per capita)	EIA
REN	Renewable energy consumption	(quad Btu per capita)	EIA
AVS	Services, value added (% of GDP)	value added (% of GDP)	WDI
GDP	Gross domestic product per capita	Constant 2015 US$	WDI
TO	Trade openness	The ratio between the sum of exports and imports and GDP	WDI

Notes: WDI: World Development Indicators; EIA: Energy Information Administration;IMF: International Monetary Fund, quad Btu: A "quad" is short for "quadrillion" (10^15) British thermal units (Btu). One Btu is the amount of energy needed to raise the temperature of one pound of water by one degree Fahrenheit.

Table 3
Summary statistics.

	MEAN	SD	MIN	MAX
LCF	0.5227271	0.2497274	0.1069692	1.373913
GDP	4934.777	5985.958	465.7263	32,786.69
TO	52.75947	27.85887	9.135846	186.4289
REN	0.2016379	0.19087	0.0045774	1.184251
NREN	3.292117	2.835859	0.1311463	11.8863
AVS	49.21384	6.452941	29.7406	61.80759

the service sector to economic output. These statistics provide a glimpse into the dataset's characteristics and dynamics, aiding in understanding the variables' distribution and range.

The correlation matrix presented in Table 4 illustrates the relationships between the variables under consideration. This matrix provides valuable insights into how each variable correlates with the others, helping to identify potential linear relationships and areas for further investigation.

To evaluate the normality of the dataset (Fig. 1), a Jarque-Bera test was performed. The obtained Jarque-Bera statistic was 5.5, accompanied by a p-value of 0.6. Given that this p-value exceeds the commonly accepted significance level of 0.05, we do not reject the null hypothesis regarding normality. This indicates that the data does not substantially differ from a normal distribution, allowing it to be treated as normally distributed for subsequent analyses.

The Fig. 2 displays the load capacity factor for various countries, indicating the efficiency of their power generation. Indonesia has the highest load capacity factor at 0.989, suggesting highly efficient energy usage. Vietnam and Nigeria follow with factors of 0.665 and 0.645, respectively. Conversely, Egypt, Turkey, and South Korea have lower efficiency, with load capacity factors of 0.235, 0.142, and 0.158, respectively. Other countries like Bangladesh, Mexico, and Pakistan exhibit moderate efficiency levels, ranging from 0.505 to 0.585.

The Fig. 3 presents the percentages of renewable and non-renewable energy consumption across various countries. Bangladesh and the Philippines have similar renewable energy usage at 14.51 % and 14.63 % respectively, with the remainder being non-renewable. Egypt and Iran rely heavily on non-renewable sources, with renewable energy making up only 4.83 % and 1.52 % of their total consumption. Indonesia's energy mix includes 4.47 % from renewables and 95.53 % from non-renewables. Mexico and Turkey show moderate renewable usage at 6.13 % and 12.91 %, respectively. Nigeria has 5.63 % renewable consumption, while Pakistan stands at 12.58 %. South Korea has the lowest renewable energy percentage at 1.19 %, relying 98.81 % on non-renewables. Vietnam shows a higher renewable share at 19.75 %, with non-renewables constituting 80.25 % of its energy use.

Conceptual Framework: This study is informed by various theoretical perspectives to establish a conceptual framework for analyzing the connections among economic growth, energy consumption, trade, and environmental sustainability. The Environmental Kuznets Curve (EKC) hypothesis suggests that as a nation's per capita income rises, its environmental pollution may initially increase before eventually declining. However, recent research has called into question the general applicability of this hypothesis, especially regarding emerging economies.The relationship between energy use and environmental quality is intricate, encompassing both direct and indirect effects. Direct effects stem from pollutant emissions during the production and consumption of energy, while indirect effects relate to resource depletion and land use changes linked to energy extraction and infrastructure development. The effects of trade on environmental quality remain a contentious issue. While trade can facilitate economic growth and technological advancement, it may also result in heightened resource consumption and pollution. The Environmental Impact Assessment (EIA) framework offers a systematic method for assessing the potential environmental consequences of trade-related activities. The significance of the service sector in promoting environmental sustainability is increasingly acknowledged. This sector can enhance environmental outcomes through innovation, efficiency improvements, and the delivery of sustainable products and services. Nonetheless, the environmental footprint of services can be considerable, particularly in industries such as transportation and construction. The load capacity factor, which assesses the relationship between biocapacity and ecological footprint, serves as a critical indicator of environmental sustainability. A declining load capacity factor indicates that human activities are surpassing the planet's regenerative capacity, resulting in environmental degradation. By synthesizing these theoretical perspectives, our study seeks to offer a thorough understanding of the factors affecting environmental sustainability in the N11 countries. Our econometric model is designed to capture the intricate interactions among economic growth, energy consumption, trade, services, and the load capacity factor, yielding valuable insights for policymakers and researchers.

In the empirical analysis, this study employs annual data from 1995 to 2021 to investigate the relationship between load capacity factor, economic growth, nonrenewable energy consumption, renewable energy consumption, services value-added, and trade openness in N11 countries. The model can be constructed based on the following formula:

$$\ln CO2_{i,t} = \beta_0 + \beta_1 \ln GDP_{i,t} + \beta_2 \ln REN_{i,t} + \beta_3 \ln NREN_{i,t} + \beta_4 AVS_{i,t} + \beta_5 TO_{i,t} + \varepsilon_{i,t} \tag{1}$$

where, t denotes the time (1995 to 2022), i denotes the 11 countries, $\varepsilon_{i,t}$ denotes a stochastic error, respectively. $\ln LCF_{i,t}$ is the log-transformed Load capacity factor, $\ln GDP_{i,t}$ is the log-transformed income per capita, $\ln REN_{i,t}$ is the log-transformed renewable energy consumption per capita,$\ln NREN_{i,t}$ is the log-transformed nonrenewable energy consumption per capita, $\ln AVS_{i,t}$ is the value of the log-transformed service added (% of GDP), and $\ln TO_{i,t}$ is the log-transformed trade openness variable. Having specified our model and collected the necessary data we proceed to the empirical process according to the following flowchart (Fig. 4).

The particular set of countries comprises 11 emerging economics (N11). That makes them to become more integrated. Thus, cross-section dependence should be tested. Failing to address this issue and assuming independence between cross-sections can lead to inaccurate, inconsistent, and biased results from estimators (Sarafidis and Wansbeek, 2012). To detect cross-section dependence, the study utilizes four CD tests Pesaran (2015); Juodis & Reese (2022); Fan et al. (2015) (Pesaran and Xie, 2021). Null hypotheses states that there is not week cross-sectional dependency between cross sections and so any shock in one variable of the countries does not affect the others.

The next step is to examine the homogeneity of the slope coefficients between the countries of interest (Pesaran & Yamagata (2008); Blomquist and Westerlund (2016); Bersvendsen and Ditzen (2021). The classical panel data model is as follows:

$$y_{i,t} = a_i + \beta'_{1,i} x_{1i,t} + \beta'_{2,i} x_{2i,t} + e_{i,t} \text{for} i = 1, 2, \ldots, n \text{and} t = 1, 2, \ldots, t \tag{2}$$

where i and t indicate the cross-section dimension and the time period respectively. Null hypothesis is formulated as:

$H_o : \beta_{2i} = \beta_2$ for some i,

against the alternative.

$H_o : \beta_{2i} \neq \beta_2$ for some $i \neq j$,

Table 4
Correlation matrix.

	ln_gdppc	ln_lcf	ln_ren	ln_nonren	ln_tr	ln_avs
ln_gdppc	1					
ln_lcf	−0.4987	1				
ln_ren	0.4547	0.0496	1			
ln_nonren	0.8225	−0.4152	0.5198	1		
ln_tr	0.3253	−0.2984	0.3737	0.2676	1	
ln_avs	0.531	−0.3747	0.216	0.4581	−0.1266	1

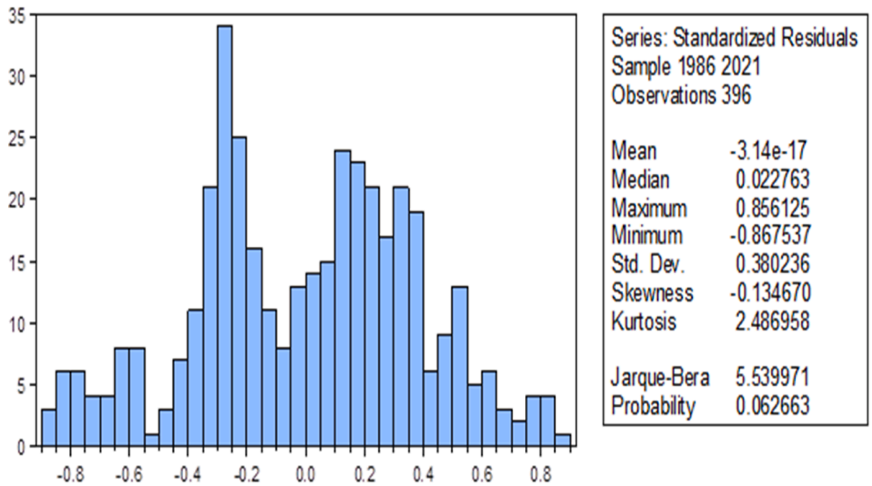

Fig. 1. Normality test.

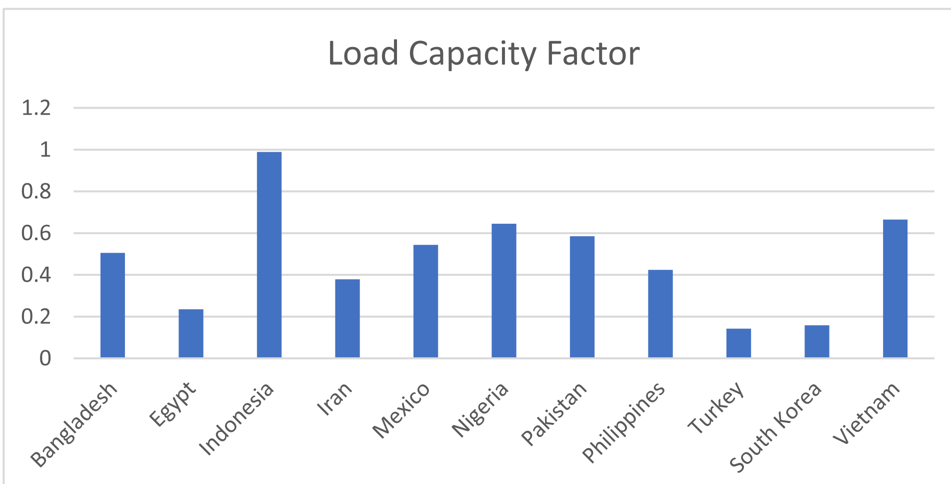

Fig. 2. Load capacity factor.

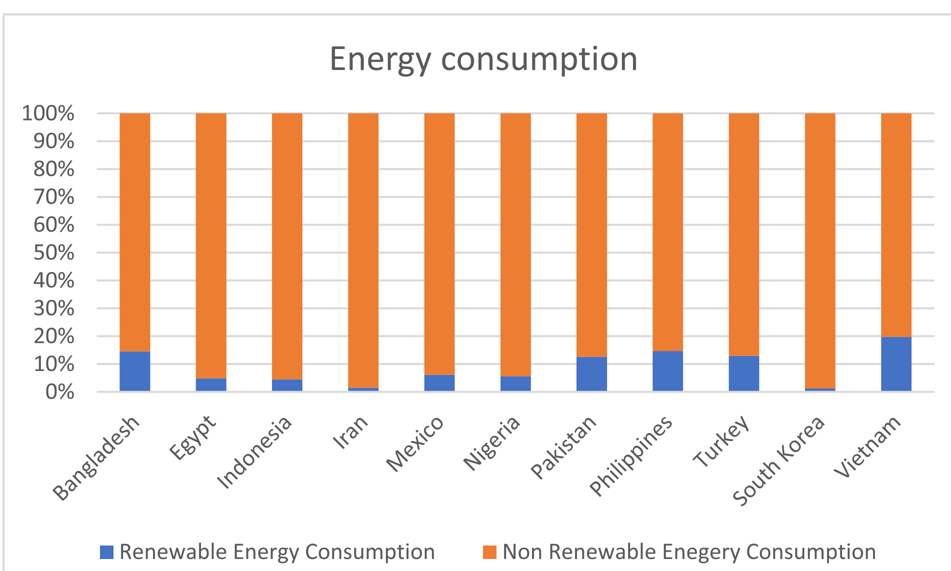

Fig. 3. percentages of renewable and non-renewable energy consumption across various countries.

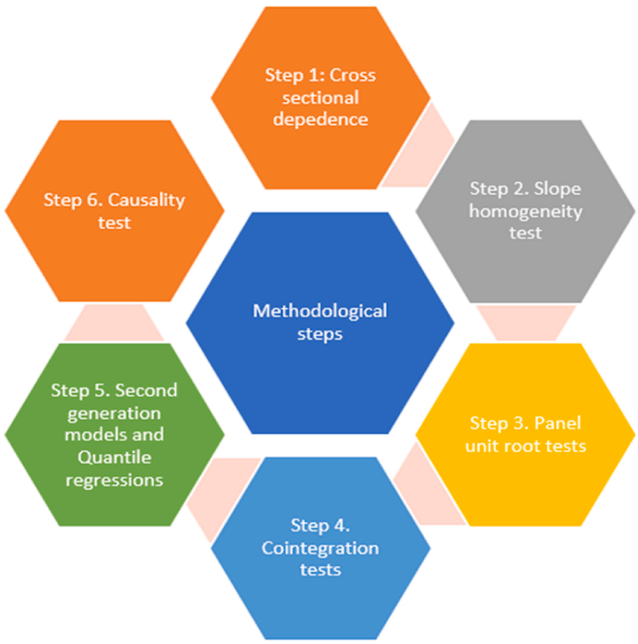

Fig. 4. Methodological scheme.

Based on delta approach, the test statistic assumes that $e_{i,t}$ and $e_{j,t}$ are independently distributed for $i \neq j$ and/or $t \neq s$. However, it allows for a heterogeneous variance. The test statistic is given by:

$$\widetilde{\Delta} = \frac{1}{\sqrt{n}}\left(\frac{\sum_{i=1}^{n}\widetilde{d}_i - k_2}{\sqrt{2k_2}}\right) \tag{3}$$

Under the null hypothesis, slope coefficients are homogeneous across cross-sectional units.

Thereafter, to examine the stationarity hypothesis of the panel series employed in the present study, we should use the appropriate unit root tests. Using first-generation panel unit root tests that rely on cross-sectional independence and do not allow for a heterogenous cross-sectional slope coefficient in modeling is inappropriate as these methods can lead to inaccurate conclusions. To address these issues, this study employs the cross-sectionally augmented Dickey-Fuller (CADF) panel unit root tests developed by Pesaran (2007). Therefore, in the following step of analysis, the cross-sectional augmented Dickey-Fuller (CADF) and cross-sectional IPS (CIPS) unit root tests developed by Pesaran (2007) should be utilized. CIPS test is a modified IPS test specified as follows:

$$CIPS = \frac{1}{n}\sum_{i-1}^{n} CADF_i \tag{4}$$

where *CADF* is the individual augmented Dickey-Fuller test that is described below:

$$\Delta y_{i,t} = a_i + \rho_i y_{i,t-1} + \beta_i \overline{y}_{t-1} + \sum_{j=0}^{k}\gamma_{i,j}\Delta\overline{y}_{t-1} + \sum_{j=0}^{k}\gamma_{i,j}\Delta y_{t-1} + e_{i,t} \tag{5}$$

where a_i, k and y ¯_t are the constant, the lag specification and the temporary defined cross-sectional average respectively. The null hypothesis considers that variables are not stationary. If variables are integrated, the group of selected variables may be cointegrated in the long-run time horizon. After that, this study employs several panel cointegration approaches, specifically the demeaned options of Pedroni (1999; 2004), Pedroni [1999] and Kao (1999), the bootstrapping Westerlund (2005) to assess the possible long-run relationships between the variables in the model. The aforementioned tests of cointegration can give robust results in the presence of possible heterogeneity and cross-sectional dependence following the bootstrapping and demean options.

After establishing a long-term equilibrium relationship between the variables, the econometric analysis progresses by employing cointegration models. In our study, we utilize 1st and 2nd generation models, starting with the fixed-effects (FE), fully modified ordinary least squares (FMOLS), and dynamic ordinary least squares (DOLS). More specifically, the current study estimates the fixed effects with Driscoll & Kraay (1998) standard errors (FE-DK) technique that provides robust estimates in the existence of heteroskedasticity, cross-sectional and serial dependence (Sarkodie and Strezov 2019). Moreover, since our data is an extended and heterogenous panel dataset, we employ three alternative estimations. First, the fully modified ordinary least squares (FMOLS) estimator suggested by Phillips and Hansen (1990), as it addresses endogenous and serial correlation errors. Second, the dynamic ordinary least squares (DOLS) estimator proposed by Saikkonen (1991) and Stock and Watson (1993) is employed as it addresses endogeneity while giving normally distributed estimators. Last, this study uses the innovative Machado & Silva (2019) quantile regressions (MMQR) method to find the distributional and heterogenous effects across quantiles while addressing cross-sectional dependence.

As a final step, to ascertain the causal relationship between the predicted variable and different predictors, the study also incorporates the recent Granger causality method proposed by Juodis et al. (2021). The distinctiveness of this technique lies in its approach: under the null hypothesis, although individual effects and autoregressive parameters can vary among individuals, the Granger-causation parameters are uniformly zero, indicating homogeneity (Xiao et al., (2023)). Null hypothesis defines absence of causal relationship between variables for all cross-sections while the alternative hypothesis assumes that there can be causal relationship between variables of some groups.

4. Results

Beginning with the cross-sectional observations outlined in Table 5 (panel A), the research outcomes (CD, CDw, CDw+, and CD*) challenge the notion of cross-sectional independence across all studied variables. Furthermore, the results of slope homogeneity tests in Panel B reject the assumption of uniform slopes, suggesting variations in coefficients among different countries.

In light of these results, it is recommended to conduct the panel unit root test using the second-generation estimation method (CADF), which considers country-specific variations within the dataset. The outcomes of the panel unit root tests are detailed in Table 6.

The results from the CADF test indicate that all examined variables

Table 5
Cross-section dependence (Panel A) and slope homogeneity tests (Panel B).

Panel A: Cross-section dependence				
Variables	**CD**	**CD_W**	**CD_{W+}**	**CD_{W^*}**
LnLCF	37.29***	5.08***	281.6***	0.52
lnGDP	41.41***	5.88***	313.0***	−4.99***
lnREN	32.94***	3.58***	247.8***	−1.26
lnNREN	42.00***	5.48***	316.9***	−16.46***
lnTO	11.25***	4.18***	142.6***	1.08
lnAVS	13.31***	−0.68***	146.1***	4.46***
Panel B: Slope homogeneity tests				
Statistic			Δ	Δ_{adj}
			16.808***	18.726***
p-value			0.000	0.000

Notes: ***, ** and * denote 1 %, 5 % and 10 % significance level, respectively. CD (Pesaran, 2021; Pesaran, 2015); CD_W (Juodis and Reese, 2022); CD_{W+} (Fan et al., 2015) CD_{W^*} (Pesaran and Xie, 2021). Δ denotes the first difference operator.

Table 6
Panel unit root tests.

Variables	CADF	Variables	CADF
LnLCF	−2.32	ΔlnLCF	−3.43***
lnGDP	−2.01	ΔlnGDP	−3.02***
lnREN	−1.84	ΔlnREN	−4.88***
lnNREN	−2.04	ΔlnNREN	−3.92***
lnTO	−1.96	ΔlnTO	−4.01***
lnAVS	−2.13	ΔlnAVA	−4.00***

Notes: ***, ** and * denote 1 %, 5 % and 10 % significance level, respectively. Δ denotes the first difference operator. All the variables in level were tested with intercept and trend. Pesaran's CADF test presents *Z t*-bar values.

are non-stationary at the 0.05 or 0.1 significance level. However, all variables exhibit stationarity at the 1 % significance level when differenced once. As a result, we can deduce that the variables are integrated at order 1 (I(1)) and do not display unit root issues. This section provides insights into the cointegration relationship among the considered variables.

Table 7 presents the outcomes of the conducted cointegration tests, indicating the presence of a long-run relationship relating load capacity factor, real gross domestic product, renewable energy consumption, non-renewable energy consumption, services value-added, and trade openness. With these variables cointegrated, we can proceed to estimate the long-term relationships among the variables of interest.

Table 8 presents the results of various regression models using different estimation techniques, focusing on the variables lnGDP, lnREN (renewable energy consumption), lnNREN (nonrenewable energy consumption), lnTO (trade openness), and lnAVS (services value-added). Each model is denoted by its respective estimation method: Fixed Effects (FE), FE-with DK, Fully Modified Ordinary Least Squares (FMOLS), and Dynamic Ordinary Least Squares (DOLS).

In the FE model, lnGDP is negatively associated with the load capacity factor, indicated by the negative coefficient (−0.344), which is statistically significant at the 1 % level. Similarly, lnREN has a positive coefficient (0.068), indicating a positive impact on the load capacity factor. On the other hand, lnNREN and lnTO both show negative coefficients (−0.260 and −0.073, respectively), implying a negative influence on the load capacity factor.Moving to the FE-with DK model, the coefficients for lnGDP, lnREN, lnNREN, and lnTO remain consistent with the FE model but introduce slight variations, as indicated by the standard errors in parentheses.

In the FMOLS model, lnGDP maintains a negative impact on the load capacity factor, although the coefficient is reduced (−0.170), but still significant at the 1 % level. Conversely, lnREN shows a slightly increased positive impact (0.061), while lnNREN has a substantially negative coefficient (−0.785), implying a strong negative effect. Additionally, lnTO continues to display a negative impact with a coefficient of −0.091.

Table 7
Panel cointegration tests.

Pedroni [2,3] with constant and trend	*Statistic*	*P-value*
Modified Phillips-Perron t	0.3064	0.3797
Phillips-Perron t	−6.4618***	0.0000
Augmented Dickey-Fuller t	−6.0014***	0.0000
Kao [4] with constant		
Modified Dickey-Fuller *t*	−2.860***	0.002
Dickey-Fuller t	−3.577***	0
Augmented Dickey-Fuller t	−2.928***	0
Unadjusted modified Dickey-Fuller t	−5.504***	0
Unadjusted Dickey-Fuller t	−4.569***	0
Westerlund [37] with constant and trend	*Statistic*	*P-value*
Variance ratio	−1.454*	0.072

Notes: ***, ** and * denote 1 %, 5 % and 10 % significance level, respectively. Kao-ADF, Pedroni-PP and Pedroni ADF indicate ADF based on Kao (1999) and PP based and ADF based test of Pedroni (1999; 2004). Variance ratio statistic stands for cointegration test of Westerlund (2007). Pedroni and Westerlund's cointegration vectors account for a time trend. The kernel method was utilized to estimate the long-run variance for each series within the panel.

Table 8
Regression models.

Variables	FE	FE-with DK	FMOLS	DOLS
lnGDP	−0.344***	−0.344***	−0.170***	−0.254***
	(0.050)	(0.080)	(0.044)	(0.059)
lnREN	0.068***	0.028***	0.061***	0.046***
	(0.018)	(0.018)	(0.011)	(0.013)
lnNREN	−0.260***	−0.260***	−0.785***	−0.668***
	(0.028)	(0.033)	(0.047)	(0.051)
lnTO	−0.073***	−0.073***	−0.091***	−0.081*
	(0.019)	(0.013)	(0.028)	(0.042)
lnAVS	0.313***	0.313***	0.097	0.195***
	(0.075)	(0.010)	(0.039)	(0.068)

Notes: ***, ** and * denote 1 %, 5 % and 10 % significance level, respectively. Numbers in parentheses represent standard errors. All variables are expressed in a natural logarithm.

Lastly, the DOLS model presents different results, with lnGDP having a larger negative coefficient (−0.254) compared to the FE and FMOLS models. Both lnREN and lnNREN demonstrate positive coefficients (0.046 and −0.668, respectively), indicating contrasting effects on the load capacity factor. Furthermore, lnTO shows a significant negative impact (−0.081), although with a smaller magnitude compared to the other models. Overall, the regression models provide valuable insights into the relationships between economic, energy-related, and trade variables and their influence on the load capacity factor, contributing to a comprehensive understanding of environmental sustainability dynamics.

In Table 9, the coefficients for lnGDP vary across quantiles, suggesting that the impact of gross domestic product on sustainability differs based on the position within the load capacity distribution, with a more pronounced negative effect observed at higher load capacity levels (quantile 0.75). We opted for the quintile ranges of 0.25, 0.50, and 0.75 to categorize the load capacity factor data into equal groups, facilitating a thorough analysis of the relationships among variables at various levels of environmental stress. These quintiles correspond to the 25th, 50th, and 75th percentiles of the LCF distribution, creating a clear and interpretable segmentation of the data. This method allows us to discern how the impacts of economic growth, energy composition, trade openness, and the value-added from services differ across varying degrees of environmental pressure.

Similarly, the positive coefficients for lnREN across quantiles imply that the influence of renewable energy consumption on the load capacity factor is stronger at lower and median load capacity levels (quantiles 0.25 and 0.50), gradually decreasing as load capacity increases (quantile 0.75). Conversely, the negative coefficients for lnNREN demonstrate a stronger negative impact of nonrenewable energy consumption on sustainability at higher load capacity levels (quantile 0.75), indicating that higher nonrenewable energy consumption exacerbates sustainability

Table 9
Quantile regression models (MMQR).

Variables	0.25	0.50	0.75
lnGDP	−0.346***	−0.344***	−0.342***
	(0.065)	(0.053)	(0.079)
lnREN	0.070***	0.068***	0.065**
	(0.025)	(0.020)	(0.030)
lnNREN	−0.237***	−0.259***	−0.283***
	(0.042)	(0.031)	(0.048)
lnTO	−0.051*	−0.072***	−0.095***
	(0.028)	(0.034)	(0.034)
lnAVS	0.276**	0.311***	0.351***
	(0.111)	(0.091)	(0.135)

Notes: ***, **, and * denote 1 %, 5 %, and 10 % significance level, respectively.

Table 10
Panel Granger causality tests.

H_0	HPJ Wald-Stat	BIC selection
lnGDP does not Granger-cause lnLCF	9.112***	−2108.3*(1 lag)
LnLCF does not Granger-cause lnGDP	2.131	−2.555.8*(1 lag)
lnREN does not Granger-cause ln LCF	13.832***	−2087.4*(1 lag)
ln LCFdoes not Granger-cause lnREN	17.284***	−1298.2*(1 lag)
lnNREN does not Granger-cause ln LCF	12.349***	−2139.8*(1 lag)
ln LCF does not Granger-cause lnNREN	0.000	−2065.51*(1 lag)
lnTO does not Granger-cause ln LCF	35.164***	−2080.1*(1 lag)
ln LCF does not Granger-cause lnTO	0.109	−1460.1*(1 lag)
lnAVS does not Granger-cause ln LCF	0.885	−2086.3*(1 lag)
ln LCFdoes not Granger-cause lnAVS	3.16*	−2472.8*(1 lag)

challenges..

The Granger causality findings from Juodis et al. (2021) highlight a bidirectional relationship at a 5 % significance level between Load Capacity Factor (LCF) and economic growth. Similarly, the feedback hypothesis is substantiated between renewable energy consumption and LCF at a 1 % significance level. It's worth noting that there is a significant one-way causality from non-renewable energy consumption to LCF. Conversely, a unidirectional causality from LCF to Services Added Value (SAV) is evident. Lastly, a significant unidirectional causality is detected from Trade Openness (TO) to LCF.

5. Discussion

The results presented showcase the diverse impacts of economic, energy-related, and trade variables on the load capacity factor, crucial for understanding environmental sustainability dynamics. Across different regression models, distinct patterns emerge. Notably, lnGDP consistently exhibits a negative association with the load capacity factor, underscoring challenges posed by economic growth to sustainability. The results regarding the relationship between GDP and LCF align with previous studies by Pata and Samour [10], Alola et al. [11], Guloglu et al. [23], Shang et al. [25], and Fareed et al. [26]. The consistency in findings across multiple studies underscores the inverse relationship between GDP and LCF, indicating that as GDP increases, load capacity factor tends to decrease. This alignment strengthens our understanding of the complex dynamics between economic growth and energy utilization, highlighting the importance of considering GDP as a significant factor in energy-related research.

Conversely, lnREN (renewable energy consumption) displays a positive impact, highlighting the potential of renewable energy sources in enhancing sustainability efforts. The results are in accordance with previous literature, such as Alola et al. [11] and Guloglu et al. [23]. On the contrary, lnNREN (nonrenewable energy consumption) and lnTO (trade openness) demonstrate negative influences, indicating environmental drawbacks associated with increased nonrenewable energy use and higher trade openness levels. The findings align with Alola et al. [21], indicating a negative impact of trade openness on environmental quality. However, they diverge from Sabir and Gorus [8] and Kongbuamai et al. [20], suggesting potential variations in methodology or contextual factors contributing to these contrasting results. Additionally, the negative impact of non-renewable resources on the environment, as found in Pata and Isik [9], is consistent with expectations.

The varying coefficients for lnGDP at different quantiles suggest a more pronounced negative effect of GDP on sustainability at higher load capacity levels, possibly due to increased resource demands and environmental pressures associated with economic growth. In contrast, the positive coefficients for lnREN imply that the positive impact of renewable energy consumption is more prominent at lower and median load capacity levels, indicating the potential for renewable energy to mitigate sustainability challenges, particularly in less resource-intensive contexts. Conversely, the negative coefficients for lnNREN highlight the exacerbation of sustainability challenges with higher nonrenewable energy consumption, especially evident at higher load capacity levels where resource depletion and environmental degradation are more pronounced.

Regarding lnTO, the negative coefficients across quantiles signify a consistent adverse effect of trade openness on sustainability, which is more pronounced at higher load capacity levels (quantile 0.75), suggesting that increased trade openness may lead to higher environmental pressures. Lastly, the positive coefficients for lnAVS indicate a positive association between services value-added and sustainability, with a stronger positive impact observed at higher load capacity levels (quantile 0.75), suggesting that higher value-added from services contributes positively to environmental sustainability, especially at higher load capacity levels. Similarly, similar results to our study regarding the positive impact of services added value (AVS) on environmental quality have been found by Rafiq et al. (Rafiq et al., 2016). Their comprehensive study, covering 53 countries over the period from 1980 to 2010, examined various factors including CO2 emissions, total population, GDP per capita, industrialization, service sector contributions to GDP, and agricultural sector contribution to GDP. The results from nonlinear estimations revealed that industrialization contributed to increased pollution levels, while both service and agriculture value added were associated with reductions in emissions.

Table 11 presents the groups of countries corresponding to each quantile. This classification helps in understanding the distribution of countries based on the specified quantiles, with distinct groupings observed for quantiles 0.25, 0.50, and 0.75.

A bidirectional relationship between Load Capacity Factor (LCF) and economic growth indicates that changes in economic growth can influence LCF, and vice versa. The validation of the feedback hypothesis between renewable energy consumption and LCF implies a dynamic interaction where changes in renewable energy consumption affect LCF, and the feedback from LCF also impacts renewable energy consumption. The significant one-way causality from non-renewable energy consumption to LCF suggests that increases or decreases in non-renewable energy consumption may directly affect LCF. Conversely, the unidirectional causality from LCF to Services Added Value (AVS) implies that changes in LCF may have a direct impact on AVS, potentially reflecting the economic benefits derived from load capacity optimization. Finally, the significant unidirectional causality from Trade Openness (TO) to LCF indicates that changes in trade openness can influence LCF without reciprocal effects, highlighting the role of international trade dynamics in shaping load capacity factors. All statistically significant variables discussed are presented in Fig. 5.

6. Conclusions

In conclusion, our study provides empirical insights into the environmental sustainability dynamics within the N11 countries, leveraging a comprehensive methodological framework and rigorous econometric analyses. Our findings reveal significant relationshipsbetween economic activities, energy consumption patterns, trade openness, and environmental sustainability metrics.

Firstly, the stability of the data is confirmed by the CADF test, indicating that all examined variables are integrated at order 1 (I(1)). Additionally, compelling evidence of a long-term association among the load capacity factor, real GDP, renewable and non-renewable energy consumption, services value-added, and trade openness supports the presence of cointegration relationships crucial for understanding

Table 11
Group of countries by quantile distribution.

Quantile	Countries
0.25	Egypt, South Korea, Turkey, Iran
0.5	Bangladesh, Nigeria, Philippines, Mexico, Pakistan
0.75	Indonesia, Vietnam

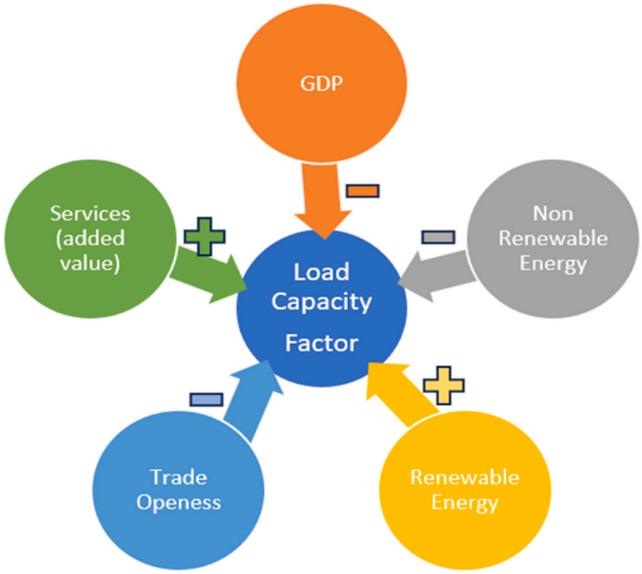

Fig. 5. Estimated relationships between the variables of interest.

sustainability dynamics.Furthermore, our regression models elucidate the nuanced impacts of economic, energy-related, and trade variables on the load capacity factor. Notably, non-renewable energy consumption consistently exhibits a negative association with the load capacity factor across various model specifications, emphasizing the detrimental effects of non-renewable energy sources on environmental sustainability. Conversely, renewable energy consumption shows a positive impact on the load capacity factor, indicating the potential for sustainable energy solutions to mitigate environmental pressures.Moreover, the quantile regression analysis reveals variations in the effects of gross domestic product (GDP), renewable and non-renewable energy consumption across different quantiles of the load capacity distribution, providing valuable insights into the differential impacts of economic and energy variables on sustainability.

Lastly, the Granger causality findings underscore bidirectional relationships between economic growth and the load capacity factor, as well as significant causal links from renewable and non-renewable energy consumption to the load capacity factor, and from trade openness to the load capacity factor.Overall, these empirical findings contribute to a deeper understanding of sustainability dynamics in the N11 countries, offering valuable insights for policymakers and stakeholders. By leveraging robust analytical tools and rigorous empirical assessments, our research provides actionable recommendations for fostering environmental sustainability while promoting economic growth and societal well-being in the N11 countries.

In the lowest quantile (0.25), we observed that economic growth exerted a more significant negative effect on the load capacity factor than in the higher quantiles. This indicates that, in nations experiencing lower levels of environmental pressure, economic growth may present greater sustainability challenges. At the median quantile (0.50), the beneficial impacts of renewable energy consumption on the load capacity factor were more evident compared to both the lowest and highest quantiles. This finding suggests that renewable energy can significantly help alleviate environmental pressures in countries facing moderate levels of stress.In the highest quantile (0.75), the detrimental effects of non-renewable energy consumption and trade openness on the load capacity factor were notably stronger than in the lower quantiles. This implies that in countries with elevated levels of environmental pressure, a greater reliance on non-renewable energy sources and increased trade openness may worsen sustainability issues.

The results from this paper offer crucial policy implications for decision-makers and stakeholders in the N11 countries. The detrimental effects of non-renewable energy consumption and trade openness on the load capacity factor (LCF) stress the urgent need to transition to sustainable energy sources and implement strategies to mitigate the environmental impacts of increased trade. Policymakers are advised to prioritize investments in renewable energy infrastructure and promote sustainable trade practices to enhance environmental sustainability and support economic growth. Additionally, the positive link between services value-added (AVS) and sustainability indicates that policies encouraging the development of service-oriented sectors can help align economic activities with environmental targets.Building upon the insights garnered from this study, future research endeavors could delve deeper into several avenues to enrich the understanding of sustainability dynamics. Firstly, exploring the nuanced impacts of specific renewable energy sources on the load capacity factor could provide valuable insights into optimizing energy transition strategies.

To tackle the environmental issues linked to economic growth and energy consumption, governments should focus on boosting investments in renewable energy infrastructure, establish carbon pricing systems, and encourage energy efficiency initiatives. Furthermore, policies that promote sustainable consumption habits and reduce dependence on resource-intensive sectors can help alleviate the negative effects on the load capacity factor. From a societal standpoint, it is essential for policymakers to ensure that the shift toward a more sustainable economy is both fair and inclusive, addressing potential inequalities and offering support to vulnerable groups. By embracing a comprehensive strategy that integrates the social, economic, and environmental aspects of sustainability, policymakers can pave the way for a more resilient and thriving future for the N11 nations.

While our study provides valuable insights into the relationship between economic growth, energy consumption, trade, and environmental sustainability in the N11 countries, it is important to acknowledge certain limitations. First, the availability and quality of data can affect the accuracy and generalizability of our findings. Second, our analysis is based on a specific set of variables, and there may be other factors that influence environmental sustainability that we did not consider. Third, the cross-sectional nature of our data limits our ability to establish causality definitively. Future research could address these limitations by using more comprehensive datasets, incorporating additional variables, and employing longitudinal analysis techniques.

Moreover, investigating the role of regulatory frameworks and policy instruments in influencing sustainability outcomes across diverse economic contexts would contribute to designing effective policy interventions. Additionally, longitudinal studies tracking sustainability indicators over time and incorporating broader geographical scopes could enhance the generalizability and robustness of findings, offering comprehensive perspectives on global sustainability challenges and opportunities. Future research may benefit from exploring alternative methodologies or expanding the scope of variables to further investigate the impact of technological innovation on sustainable development, as our analysis did not yield statistically significant outcomes in this regard. Finally, future research could consider conducting country-specific analyses or incorporating additional contextual variables to enhance the applicability of the findings across the N11 countries.

Author contributions

D.P. formulated the research idea, collected the data, and carried out statistical and econometric analysis.

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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

Data will be made available on request.

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