

How do renewable energy adoption and forest area conservation enhance climate resilience? New empirical evidence from developing economies

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Abstract

Purpose – In the niche of growing concerns about ensuring environmental sustainability, it is necessary to explore such strategies that enhance climate resilience (CMR). In this wake, this study aims to disclose the potential impacts of renewable energy adoption (REA) and forest area conservation (FRA) on CMR. Specifically, this study analyzes how both REA and FRA impact the climate vulnerability (CVN) situation in a country.

Design/methodology/approach – The empirical analysis was settled on South Asian economies throughout 1999–2023. This study uses the cross-sectional autoregressive distributed lag model as a primary estimation technique and checks the robustness through the fully modified ordinary least squares model.

Findings – The findings infer that both REA and CMR negatively (positively) affect CVN (CMR), thereby enhancing environmental sustainability. More reliance on renewable energy and exploration of forests significantly reduces carbon emissions and enhances the availability of fresh air. Moreover, the forest area absorbs carbon emissions, thereby enhancing the quality of air. These findings remain consistent even after including the control variables and using the alternative estimation technique.



Practical implications – The findings advocate important policy suggestions regarding the focus on the adoption of renewable energy as fuel inputs and enhancing the area of forests.

Originality/value – This study offers novel evidence by considering both REA and FRA in a single setting of study.

Keywords Climate resilience, Climate vulnerability, Forest area conservation, Renewable energy adoption, South Asia

Paper type Research paper

1. Introduction

In the temp of an increasing focus on environmental sustainability and carbon mitigation, it is necessary to adopt such strategies that help in achieving such objectives. Among others, the adoption of sustainable energy options and enhancing the forest are the key strategies that may align with these aims (Khurshid *et al.*, 2024; Shang *et al.*, 2024). To adopt these strategies, it requires fostering efforts toward early mitigation of environmental impacts and consumption of fossil fuels. Moreover, widespread socioeconomic and environmental disruptions have resulted from the intensifying effects of climate change. These issues disproportionately affect vulnerable communities, especially those in developing countries, where they face various calamities in the shape of increased droughts, floods and biodiversity losses. These extreme events lead to food security issues, public health concerns and economic instability. These decisions are impacted by climate resilience (CMR), making it more than just an environmental issue (Raihan *et al.*, 2024). Therefore, the need for comprehensive strategies to improve resilience is highlighted by the SDGs of the UN, especially SDG 13 (Climate Action), which places a strong emphasis on integrating sustainable land management techniques with renewable energy technology. Leaning on these arguments, the current analysis focuses on how adoption of renewable energy (REA hereafter) and forest area conservation (FRA) reduces the climate vulnerability (CVN), thereby enhancing the CMR.

Referring to the main theme of the study, CMR is the capacity of ecological, social and economic systems to adapt, recover and prosper in the face of climate change challenges (Cousins, 2024; Rodríguez and Carril, 2024). Owing to escalating concerns on climate sustainability, CMR has become a top global priority. The need to increase resilience against these threats is highlighted by rising temperatures, changing weather patterns and an increase in the frequency of extreme weather events. Therefore, adoption of renewable energy and the preservation of forest areas stand out among the many strategies being investigated as two crucial tactics with broad implications for reducing climate risks and improving adaptive capacities. In the same context, REA is the system of incorporating renewable energy technologies such as geothermal, hydro, wind and solar. Specifically, it entails switching from fossil fuels to more sustainable clean energy sources to lower greenhouse gas emissions and improve energy security. REA ensures that all energy inputs align with the broader goal of minimum environmental impacts and fewer negative externalities generated from combustion and production of industrial goods (Horky and Fidrmuc, 2024). Apart from land primarily used for agriculture or urban purposes, a forest area is generally defined as land that is more than 0.5 hectares in size, has trees taller than 5 meters and has a canopy cover of more than 10%. Forests are essential for ecosystem services, biodiversity preservation and carbon sequestration (Savari and Khaleghi, 2024).

The impact of both REA and FRA can be explained in a number of ways to help us better understand their possible roles in CMR. The FRA and the REA, for example, are crucial elements of CMR because they provide complementary strategies for reducing the effects of

climate change and preparing for them. By promoting sustainable development, reducing greenhouse gas emissions and safeguarding ecosystems, these strategies address the causes and consequences of climate change. Positive integration of renewable energy and forest conservation holds great promise for creating a resilient and sustainable future. However, implementation challenges must be overcome through cooperation, ingenuity and steady funding to accomplish this goal. REA contributes to the reduction of greenhouse gas emissions, which decreases the intensity and frequency of extreme weather events and the primary causes of climate change (Khoury *et al.*, 2025). This change also encourages energy independence by ensuring decentralized reliable energy systems that are resilient to climate-related disruptions (Panait *et al.*, 2024). When it comes to maintaining ecosystem services such as soil fertility, water purification and disaster risk reduction, FRA serves as a natural buffer by storing carbon, controlling local temperatures and preserving biodiversity. By reducing exposure to climate hazards, stabilizing agricultural productivity through ecosystem regulation and creating green jobs, these policies foster socioeconomic resilience. Additionally, the combination of REA and FRA enhances adaptive capacities and offers a comprehensive strategy for mitigating the effects of climate change and ensuring the long-term viability of ecosystems and communities by combining technological advancement with environmental preservation.

The study found how CMR is affected by the adoption of renewable energy (REA) and the conservation of forest areas (FRA). South Asian economies were the subject of an empirical analysis using the cross-sectional autoregressive distributed lag (CS-ARDL) and fully modified ordinary least square (FMOLS) models from 1999 to 2023. The results suggested that FRA and REA both have a detrimental effect on CVN, demonstrating their beneficial effects on CMR. In addition, the analysis yields the dynamic impact of economic growth, FDI inflow, banking development and accountability quality on CMR, thereby highlighting the contribution of other economic and social factors in achieving environmental sustainability. Adoption of renewable energy directly lessens the negative effects of climate change by lowering greenhouse gas emissions, increasing energy efficiency and fostering a cleaner energy matrix, all of which lower exposure to risks associated with climate change. But by storing carbon, stopping soil erosion and preserving hydrological cycles, all of which are essential for lessening the effects of floods, droughts and other natural disasters, FRA acts as a natural barrier. When taken as a whole, these actions improve CMR by maintaining ecosystem stability and encouraging sustainable development.

The study contributed in many ways. By combining the dual pillars of environmental sustainability, i.e. REA and FRA, this study advances theoretical understanding of CMR. By bridging the gap between technological advancements and ecological conservation, it enhances the body of existing literature by providing a thorough framework that highlights their complementary effects on lowering CVN. While prior studies have typically examined the impact of either REA or FRA in isolation on environmental sustainability (Ansari, *et al.*, 2024; Seo, *et al.*, 2025), this study offers a novel integrated approach by jointly analyzing the effects of both REA and FRA on CMR within the same empirical framework. This dual-variable setting allows for a more comprehensive understanding of how natural (forests) and technological (renewable energy) strategies interact to mitigate CVN in developing economies. To achieve CMR, the study presents strong theoretical insights into the dynamic interaction between environmental, economic and governance factors using sophisticated econometric techniques such as CS-ARDL and FMOLS. It also expands on the theoretical discussion of how economic growth, institutional quality and FDI shape adaptive capacities, showing how multiple dimensions work together to affect environmental sustainability.

The study empirically offers evidence-based insights into how REA and FRA affect CMR in the particular context of South Asian economies for the years 1999–2023. It establishes a causal relationship between these factors and their capacity to reduce CVN by using panel data and rigorous econometric models. These empirical findings provide fresh insights into the interplay between socioeconomic and governance factors and environmental policies in addition to validating preexisting theoretical frameworks. Additionally, by concentrating on an area that is particularly vulnerable to climate risks. The study deepens the global conversation on environmental sustainability by providing context-specific insights that can be applied to other developing economies dealing with comparable issues.

This study has significant practical ramifications and offers businesses, development organizations and policymakers practical suggestions. The results highlight the importance of advancing conservation initiatives and renewable energy policies for policymakers to improve CMR. These consist of encouraging clean energy investments, growing forest conservation programs and incorporating these actions into regional and national climate policies. The study emphasizes the significance of implementing sustainable practices and green technology adoption for businesses to lower operational risks related to climate change. Development organizations and financial institutions can also use the study's findings to create focused interventions that address the twin goals of economic growth and environmental preservation, such as green finance plans, public–private partnerships and capacity-building initiatives (Janjua *et al.*, 2024). Finally, by combining cutting-edge technologies, environmental conservation and inclusive economic policies, the study offers a roadmap for building a future that is climate resilient.

Other parts of papers are sequenced as follows. Section 2 is a literature review, Section 3 is of data and methods, Section 4 is of results and Section 5 consists of results discussion. In Section 6, the conclusion of the study and policy implications are presented.

2. Literature review

To suppose the relationship between the variables, the review of literature can be segregated into the following parts.

2.1 Renewable energy adoption and climate resilience

Khan *et al.* (2020) examined the relationship between various factors, including renewable energy consumption (REC), international trade, and environmental quality in Nordic countries over the period 2001–2018. Using advanced econometric techniques, their analysis revealed a significant positive impact of REC on international trade and environmental quality. Notably, the findings suggest that increasing renewable energy use not only fosters trade expansion but also enhances environmental sustainability. The findings mainly highlight the vital role played by REC in attaining the sustainable development goals that are in line with eco-friendly policy formulation. Another study conducted by Suman (2021) assessed the role of renewable energy technologies in addressing climate change mitigation and adaptation in Nepal. Using a review-based methodology, they examined the status, adoption potential, and impacts of various renewable energy solutions, including micro-hydro projects, solar power, biogas and improved cooking systems. The findings revealed that REA (renewable energy adoption) has significantly reduced GHG emissions. This further has positive outcomes in the shape of enhanced carbon sequestration and supported socio-economic resilience through health improvements, job creation and alternative income sources (Ionescu *et al.*, 2024).

The empirical analysis conducted by Zheng and Zheng (2023) investigated public acceptance of solar energy for residential use in the case of rural China. By using the primary

research technique, i.e. a questionnaire-based survey of 600 respondents from Hebei province and SEM for analysis, the study integrated environmental information, concern, and perceived solar energy benefits within the theory of planned behavior framework. Notably, the findings revealed that environmental information, attitudes, social beliefs, perceived efficacy, and solar energy advantages positively influence acceptance, while environmental concerns lack a direct impact. These specific impacts emphasized the need for targeted awareness campaigns and robust policy frameworks to enhance sustainability practices. [Ameer, et al. \(2024\)](#) inspected the empirical impact of environmental taxes and renewable electricity on REC in the Emerging Seven (E7) economies from 1990 to 2020. In addition to the main variables, the study includes control variables such as economic growth, carbon emissions and environmental innovation. The study analyzed the empirical nexus by using a panel data set and using MMQR. The abnormality of the data distribution influenced the choice of these models. The study's conclusions showed that the use of renewable energy is highly influenced by carbon emissions, environmental taxes and renewable electricity. On the other hand, the research indicates that environmental innovation lessens dependency on it.

[Ansari et al. \(2024\)](#) sought to examine the different factors that contribute to environmental sustainability with a focus on Pakistan. As possible factors influencing environmental sustainability in Pakistan, they took into account digital finance, financial inclusion renewable energy and institutional quality. They examined both the short- and long-term relationships between these variables using data from 2004 to 2021 and the ARDL model. The results showed that while digital finance and financial inclusion greatly lower carbon emissions, renewable energy is essential for long-term environmental sustainability. Furthermore, the relationship between digital finance and institutional quality improves sustainability outcomes, highlighting the necessity of strong institutions and creative financial solutions to address climate challenges. [Dilanchiev et al. \(2024\)](#) examined the ways in which financial systems impact sustainable development with a particular emphasis on the ways in which FDI, renewable energy and remittances shape environmental quality in the top remittance-receiving nations between 2000 and 2021. The study investigated the possible connections between these variables and carbon emissions using panel data analysis and a variety of econometric techniques such as PMG-ARDL and CS-ARDL models. The results showed that while FDI raises carbon emissions, remittances and renewable energy have an inverted U-shaped relationship that improves environmental quality once certain thresholds are met.

Recently, [Ren et al. \(2025\)](#) used a spatial panel model to examine both local and spillover effects as they examined how economic complexity affected carbon emissions in 82 countries between 2001 and 2019. According to the analysis, economic complexity enhances local carbon emissions by altering the energy structure, while improving energy efficiency lowers emissions in nearby countries. The local effects are more pronounced in economically complex countries. The findings further emphasized the need for governments to harness the environmental advantages of economic complexity through technological innovation, energy optimization, and efficiency improvements. In view of literature outcomes, it can be suggested that:

- H1. Renewable energy adoption has a significant negative (positive) relationship with climate vulnerability (climate resilience).

2.2 Forest area conservation and climate resilience

The literature has enlisted the empirical impact of FRA on climate resilience. For instance, the empirical analysis of [Cao et al. \(2024\)](#) investigated how urban forest pattern indicators

(UFIs) influence PM_{2.5} levels during polluted winter days and land surface temperature (LST) during hot summer days. They checked their impact in urban cores of Jiangsu Province, China. Using remote sensing data from MODIS and other methods, the study revealed that UFIs, such as area, shape complexity, and aggregation, significantly lead to reduced PM_{2.5} and provided cooling effects. They further observed the mediating impact of LST and PM_{2.5} depending on the season. In another empirical discourse, [Huang et al. \(2024\)](#) examined the interplay between forest rent, forest extraction, green investment, health and education expenditures and emission of pollution, specifically CO₂ emissions, within the framework of China's Carbon Neutrality Program from 1970 to 2022. They explored this empirical analysis by using a nonlinear autoregressive model and identified asymmetric cointegration among these variables, revealing that negative shocks to forest rent, green investment, and education expenditure reduce CO₂ emissions over the long term, while positive shocks have the opposite effect.

[Han et al. \(2025\)](#) analyzed the ecological impact of urban trees on carbon storage, pollution removal, and BVOC emissions in a typical city within the central Beijing-Tianjin-Hebei region using field surveys and the i-Tree Eco model. By evaluating these ecological benefits and proposing an improved tree species selection method based on the Pollution and Carbon Reduction Index (PCRI), the findings revealed the composite effects of urban trees, including net increases in ozone (O₃) and particulate matter (PM_{2.5}). The study emphasized prioritizing tree species with high PCRI values for urban tree management and air quality improvement strategies. Similarly, another study conducted by [Seo et al. \(2025\)](#) analyzed the effect of forests on pollution reduction using data from various sources such as PM and AICAN. Their empirical outcomes confirmed that forest exploration is more conducive to reducing environmental impacts by mitigating carbon emissions and absorbing environmentally hazardous nutrients from the air. Specifically, the study emphasized prioritizing tree expansion in urban cities, which is also necessary for urban tree management and improvement in air quality. Leaning on literature outcomes, it can be supposed that:

H2. Forest area conservation has a significant negative (positive) relationship with climate vulnerability (climate resilience).

3. Data and methods

3.1 Data and sample

In the pursuit of exploring the interlinkages between the variables, the study uses a sample of South Asian economies and uses a comprehensive data set over the period 1999–2023. In the South Asian economies, there are eight countries, including Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan and Sri Lanka. Fortunately, all countries stay in the sample because of the availability of complete data. The economies of South Asia were chosen as the study's sample because of their distinct susceptibility to climate change as well as their dynamic socioeconomic and environmental environment. Because of its dense population, diverse ecological systems and rapidly growing economies, South Asia is an excellent place to study the relationship between the adoption of renewable energy, forest conservation and CMR. Similar to this, the rationale behind choosing the period can be summed up as follows: to give a comprehensive understanding of long-term trends and impacts, the 1999–2023 timeframe was chosen because it includes important periods of economic growth, policy changes and environmental challenges. The availability of complete data for all eight countries during this period further strengthens the analysis's robustness and ensures that the findings are representative of the entire region. By focusing

on South Asia over this extended period, the study provides significant insights into the strategies and outcomes relevant to addressing CVN in one of the world's most climate-sensitive regions. The World Bank's WDI provided data on the variables. All variables are shown in [Table 1](#).

The study focuses on South Asian economies because of their high exposure to climate-related risks, rapid population growth, and ongoing transitions toward renewable energy. These countries offer a relevant context to analyze the dynamics between REA, FRA and CMR. However, the exclusion of other vulnerable regions such as Sub-Saharan Africa was primarily because of data availability constraints, especially regarding consistent annual data on forest area, renewable energy usage, and CVN indices over the 1999–2023 period. Future research can broaden the scope by incorporating these regions, enabling more generalized insights and comparative regional assessments.

3.2 Equations and variables

The link between variables can be demonstrated in the shape of the following equations:

$$\begin{aligned}
 CMR_{it} = & \beta_0 + \sum_{i=1}^p \alpha_1 \Delta CMR_{it-1} + \sum_{i=1}^p \beta_1 \Delta REA_{it-1} + \sum_{i=1}^p \gamma_1 \Delta ECG_{it-1} \\
 & + \sum_{i=1}^p \gamma_2 \Delta FDI_{it-1} + \sum_{i=1}^p \gamma_3 \Delta BSD_{it-1} + \sum_{i=1}^p \gamma_4 \Delta VOA_{it-1} \\
 & + \varphi_1 CMR_{it-1} + \varphi_2 REA_{it-1} + \varphi_3 ECG_{it-1} + \varphi_4 FDI_{it-1} + \varphi_5 BSD_{it-1} \\
 & + \varphi_6 VOA_{it-1} + \varepsilon_{it}
 \end{aligned} \tag{1}$$

$$\begin{aligned}
 CMR_{it} = & \beta_0 + \sum_{i=1}^p \alpha_1 \Delta CMR_{it-1} + \sum_{i=1}^p \beta_1 \Delta FRA_{it-1} + \sum_{i=1}^p \gamma_1 \Delta ECG_{it-1} \\
 & + \sum_{i=1}^p \gamma_2 \Delta FDI_{it-1} + \sum_{i=1}^p \gamma_3 \Delta BSD_{it-1} + \sum_{i=1}^p \gamma_4 \Delta VOA_{it-1} \\
 & + \varphi_1 CMR_{it-1} + \varphi_2 FRA_{it-1} + \varphi_3 ECG_{it-1} + \varphi_4 FDI_{it-1} + \varphi_5 BSD_{it-1} \\
 & + \varphi_6 VOA_{it-1} + \varepsilon_{it}
 \end{aligned} \tag{2}$$

[Equation \(1\)](#) shows both the long-term and short-term impact of REA on CMR. It further includes a list of control variables, including FDI (FDI inflow), ECG (economic growth), BSD (banking sector development) and VOA (voice and accountability). Similarly, [equation \(2\)](#) mainly reveals the impact of FRA on CMR. We

Table 1. Variables of study

Acronym	Variable	Measurement	Role
CMR	Climate resilience	Climate vulnerability index	Dependent
REA	Renewable energy adoption	Renewable energy consumption (% of total final energy consumption)	Independent
FRA	Forest area	Forest area (% of land area)	Independent
ECG	Economic growth	GDP per capita growth (annual %)	Control
FDI	FDI inflow	Foreign direct investment, net inflows (% of GDP)	Control
BSD	Banking development	Domestic credit to the private sector by banks (% of GDP)	Control
VOA	Voice and accountability	Voice and accountability: estimate	Control

Source(s): Authors' own creation

check the robustness of analysis by using the FMOLS model. Therefore, the underlying equations can be updated as follows:

$$CMR_{it} = \beta_0 + \alpha_1 REA_{it} + \beta_1 ECG_{it} + \beta_2 FDI_{it} + \beta_3 BSD_{it} + \beta_4 VOA_{it} + \varepsilon_{it} \quad (3)$$

$$CMR_{it} = \beta_0 + \alpha_1 FRA_{it} + \beta_1 ECG_{it} + \beta_2 FDI_{it} + \beta_3 BSD_{it} + \beta_4 VOA_{it} + \varepsilon_{it} \quad (4)$$

Equations (3) and (4) show the long-term impact of variables on CMR.

As an explanation of the main variables under investigation, CMR is a vital indicator of a country's ability to withstand, adapt to and recover from the adverse consequences of climate change. To quantify CMR, the CVN index is a composite metric that accounts for exposure to climate hazards as well as the capacity to adjust the sensitivity of socioeconomic and environmental systems (Edmonds *et al.*, 2020). Understanding the elements that contribute to resilience is crucial given the persistent difficulties brought on by climate change. In summary, the study examines two significant independent variables: forest area (FRA) and REA. A country's transition from fossil fuels to renewable energy sources such as wind solar, and hydropower is reflected in REA, which calculates the share of renewable energy in total final energy use. This modification reduces greenhouse gas emissions and energy insecurity, two factors that are essential for enhancing adaptive capacity. On the other hand, FRA displays the percentage of a country's land area that is covered by forests. Forests are vital to the fight against climate change because they serve as habitats for biodiversity, prevent soil erosion store carbon dioxide and maintain water cycles. By acting as natural defenses against extreme weather events such as heat waves, floods and storms, they strengthen the resilience of ecosystems and communities. The study investigates the ecological, economic and environmental mechanisms through which REA and FRA reduce CVN and advance sustainability by looking at how they impact CMR.

A set of control variables is included in the study along with the main variables of interest to give a comprehensive picture of the variables affecting CMR. The yearly growth rate of GDP per capita or economic growth (ECG) is a key indicator of a nation's ability to finance investments in climate adaptation and mitigation strategies. Governments can frequently devote funds to infrastructure development, forest preservation and renewable energy projects thanks to higher economic growth. These initiatives are crucial for boosting resilience. Similarly, the contribution of outside funding to the development of climate-resilient infrastructure and the advancement of technological innovations is represented by the inflow of FDI and is expressed as a percentage of GDP. By facilitating the transfer of resources, expertise and sustainable practices, FDI can support environmental sustainability. BSD, which is defined as the proportion of domestic credit given by banks to the private sector in relation to GDP, is another crucial control variable. An economy's capacity to finance projects such as the adoption of renewable energy sources and the preservation of forests is indicated by this indicator. Furthermore, the degree of transparency and accountability in public decision-making as well as the degree of citizen participation in governmental processes are assessed by the governance metric VOA. Implementing and upholding climate policies, rallying public support and guaranteeing fair resource distribution all depend heavily on effective governance. By including these control variables, the study acknowledges how economic, financial and institutional factors interact dynamically to shape CMR and provides thorough insights into the various approaches required to mitigate CVN. In addition, Figure 1 is showcasing the impact of underlying independent variables (left-hand side) on determined dependent variables (right-hand side).

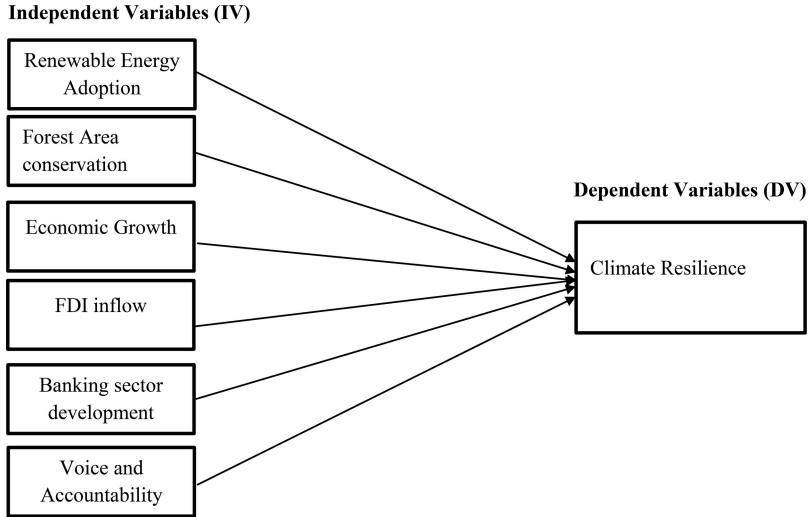


Figure 1. Research framework
Source: Authors' own creation

3.3 Methodology

In this study, we mainly use the CS-ARDL model to estimate the designed equations and check the robustness by using FMOLS mode. However, the adoption of both techniques is based upon the pre-estimation analysis offered by rigorous estimation techniques such as CD analysis and unit root testing. Table 2 and Table 3 provide a summary of the pre-estimation results, presenting the results of stationarity testing and cross-sectional dependence (CD) analysis, respectively. The significant *p*-values for the Breusch and Pesaran tests in Table 2 demonstrate that most variables have CD, with the exception of FRA (forest area), which exhibits no dependence. This result highlights how intertwined the economies of South Asia are, with common environmental and socioeconomic factors influencing the use of renewable energy, economic expansion and governance indicators. The results of the stationarity analysis using the CIPS and CADF tests are shown in Table 3. As per the findings, CMR, REA and BSD are

Table 2. Cross-sectional dependence (CD) analysis

Variables	Breusch test		Pesaran test	
	Statistic	Probability	Statistic	Probability
CMR	427.095	0.000	52.379	0.000
REA	473.952	0.000	53.712	0.000
FRA	18.903	0.231	8.918	0.328
ECG	99.703	0.000	8.512	0.000
FDI	78.464	0.000	5.644	0.000
BSD	234.322	0.000	26.051	0.000
VOA	118.017	0.000	10.960	0.000

Note(s): The acronyms can be seen in Table 1

Source(s): Authors' own creation

Table 3. Stationarity analysis

Variables	CIPS		CADF	
	At Level (0)	At first difference (1)	(0)	(1)
CMR	(0.432) 0.667	(-6.881) 0.000	(13.242) 0.654	(76.961) 0.000
REA	(0.641) 0.731	(-5.671) 0.000	(8.562) 0.931	(64.555) 0.000
FRA	(46.561) 0.000	—	(19.913) 0.000	—
ECG	(-4.931) 0.000	—	(58.658) 0.000	—
FDI	(-2.381) 0.008	—	(30.500) 0.015	—
BSD	(14.425) 0.567	(-3.622) 0.000	(0.791) 0.786	(40.441) 0.000
VOA	(23.554) 0.099	—	(26.515) 0.051	—

Note(s): The acronyms can be seen in [Table 1](#)

Source(s): Authors' own creation

among the variables that are integrated of order one ($I(1)$) because they are non-stationary at level (0) but become stationary after first differencing (1). However, it is implied that variables such as FRA, ECG and FDI are $I(0)$ because they are stationary at level. These findings support the application of estimation methods that take CD and mixed integration orders into account.

In view of the findings of pre-estimation techniques, the CS-ARDL model was chosen as the main estimation technique because of the pre-estimation analysis's compelling findings. Because of common regional factors such as policy spillovers and climate risks, South Asian economies are interconnected, as evidenced by the significant CD in most of the variables ([Table 2](#)). An excellent option for examining panel data sets with interconnected units is the CS-ARDL model, which is made to manage such dependencies by integrating cross-sectional averages. Furthermore, because the CS-ARDL model can accommodate variables integrated at different orders ($I(0)$ and $I(1)$) without requiring uniform integration levels, the mixed stationarity properties ([Table 3](#)) provide additional support for the model. The model's capacity to represent both short-term dynamics and long-term equilibrium relationships also fits in nicely with the study's goal of comprehending the long-term effects of FRA and REA on CMR. Because of its adaptability, the estimates are solid and trustworthy, taking into consideration the data sets' inherent complexity.

As a supplementary estimation method, the study uses the FMOLS model to address possible limitations of the CS-ARDL model and guarantee the robustness of the results. Because of feedback loops between variables such as economic growth, the adoption of renewable energy and CMR, the FMOLS model is especially good at handling non-stationary panel data and endogeneity problems. The need for an estimator that can handle cointegrated relationships is demonstrated by the results in [Table 3](#), which show that many variables are non-stationary at level but become stationary after first differencing. [Table 3](#) presents the results of the stationarity analysis conducted using the CIPS and CADF unit root tests. The analysis reveals that most variables, including CMR, REA and BSD, are non-stationary at level but become stationary after first differencing, confirming their integration of order one [$I(1)$]. Specifically, CMR and REA exhibit p-values above conventional significance levels at level but show strong stationarity at first difference under both tests. FRA, ECG and FDI are found to be stationary at level, suggesting they are integrated of order zero [$I(0)$]. However, VOA shows borderline stationarity, with mixed results between CIPS and CADF tests, indicating a potential need for further verification. These stationarity results confirm the suitability of applying the CS-ARDL approach for the long-run estimation, which accommodates mixed integration orders of $I(0)$ and $I(1)$, but not $I(2)$.

The estimates are efficient and objective because the FMOLS model accounts for endogeneity and serial correlation. It is important because it offers more support for the long-term connections found by the CS-ARDL model, which raises the validity and dependability of the study's conclusions.

4. Results of study

4.1 Descriptive analysis

To check the trend of data, the study checks the descriptive analysis and reports the analysis in Table 4. In Table 4, the mean value of CMR is 0.060. This suggests that although South Asian nations are making progress in adjusting to climate-related issues, much more can be done. The low standard deviation of 0.035 and the range of values from -0.019 to 0.128 indicate that resilience levels are generally consistent across these nations with few extremes. With a mean value of 47.239 , REA shows that on average almost half of South Asia's total final energy consumption comes from renewable sources. This indicates a high dependence on renewable energy, which is indicative of the area's attempts to switch to sustainable energy sources. Nonetheless, the wide range of values (1.200 – 92.000) and the high standard deviation of 27.420 highlight the notable differences between nations, some of which are heavily dependent on renewable energy while others are still in the early stages of adoption. FRA (Forest Area) also has a mean value of 24.147 , meaning that forests cover about 24% of the region's land area. Different ecological and policy contexts are reflected in the variability as shown by the range (1.852 – 71.605) and standard deviation (22.113). A few nations with significant forest cover pull the average upward, as indicated by a positive skewness (0.859).

The region's institutional and economic dynamics are further demonstrated by the control variables. With a mean GDP per capita growth of 3.485% ECG (economic growth) shows that South Asia's economy is progressing moderately. Nonetheless, the wide range of values (from -34.831 to 33.768) and the high standard deviation (6.062) demonstrate significant economic volatility, which is probably caused by changes in policy development, inequalities and external shocks. It is indicated by the negative skewness (-0.967) that below-average growth periods occur more frequently. A modest amount of foreign investment is present in the region, as evidenced by FDI inflows, which average 1.746% of GDP. Uneven patterns can be seen in the positive skewness (1.940) and standard deviation of 2.888 , which show that some nations receive disproportionately large inflows of investment. Similarly, BSD, which is a measure of financial development, has a mean value of 32.727 , indicating that the private sector has moderate access to credit. Finally, the region's governance issues are reflected in VOA, which has a mean score of -0.495 and shows that

Table 4. Descriptive statistics

Variables	Mean	Median	Max.	Min.	SD	Skewness	Kurtosis
CMR	0.060	0.059	0.128	-0.019	0.035	-0.018	2.356
REA	47.239	46.000	92.000	1.200	27.420	-0.010	2.110
FRA	24.147	18.681	71.605	1.852	22.113	0.859	2.702
ECG	3.485	3.938	33.768	-34.831	6.062	-0.967	5.322
FDI	1.746	0.765	16.783	-0.638	2.888	1.940	3.643
BSD	32.727	30.980	103.526	2.316	19.460	0.633	3.716
VOA	-0.495	-0.477	2.036	-2.031	0.560	0.341	4.176

Note(s): The acronyms can be seen in Table 1

Source(s): Authors' own creation

institutional accountability and public voice are typically low. All things considered, the descriptive statistics provide important new information about the region’s governance, economic growth, financial development, adoption of renewable energy, forest conservation and CMR.

4.2 Correlation analysis

We further check the correlation among the variables and report the statistics in [Table 5](#). As per the findings, the correlation coefficients between CMR and other variables offer important information about how different socioeconomic and environmental factors relate to CMR. CMR and REA have a negative correlation (−0.530), indicating that an increased adoption of renewable energy reduces the CVN but does not always result in an increased CMR in South Asia. This value reveals that countries with greater adoption of renewable energy sources typically have lower CVN (higher resilience) according to the negative correlation between CMR and REA. This connection highlights how renewable energy can lessen reliance on fossil fuels, reduce emissions and improve the ability to adapt to risks associated with climate change. Similarly, there is a negative correlation of −0.486 between CMR and FRA, indicating that nations with greater forest areas are less vulnerable to climate change. By controlling temperature, storing carbon and halting soil erosion, forests serve as organic barriers against climate extremes. Economic growth has little direct effect on lowering CVN as evidenced by the weakly negative correlation between CMR and ECG (economic growth) at −0.015. This may be an indication that economic expansion by itself does not considerably increase CMR in the absence of focused investments in adaptation and mitigation measures.

Conversely, there is a positive correlation between FDI and CMR of 0.250, suggesting that nations with higher FDI inflows are typically more vulnerable. This might happen if foreign investments are focused on industries that are not climate resilient or if adaptation needs are not given priority. The robust negative correlation of −0.520 between CMR and BSD emphasizes the link between less CVN and more developed banking systems. Finally, the negative correlation of −0.442 between CMR and VOA implies that reduced CVN is associated with improved governance transparency and public participation because these elements facilitate the adoption of more inclusive and successful adaptation measures. These relationships highlight the important roles those strong financial systems, forest area preservation, the use of renewable energy and sound governance play in lowering CVN and boosting resilience. To guarantee long-term sustainability, foreign investments must be in line with climate adaptation priorities as indicated by the positive correlation between CMR and FDI.

Table 5. Correlation statistics

Variable	CMR	REA	FRA	ECG	FDI	BSD	VOA
CMR	1.000						
REA	−0.530	1.000					
FRA	−0.486	0.532	1.000				
ECG	−0.015	0.061	0.084	1.000			
FDI	0.250	−0.548	−0.292	0.025	1.000		
BSD	−0.520	0.261	0.446	0.012	0.061	1.000	
VOA	−0.442	0.123	0.302	−0.034	0.099	0.638	1.000

Note(s): The acronyms can be seen in [Table 1](#)

Source(s): Authors’ own creation

4.3 Regression analysis

For regression estimation, we use the CS-ARDL model and report the results in regression Tables 6 and 7. The robustness of analysis was performed by using the FMOLS model, and findings are reported in Table 8. According to Table 6, the long-run equation REA coefficient is negative and extremely significant (-0.001), indicating that a greater use of renewable energy significantly lowers CVN. The significance of forest area in reducing climate risks is further highlighted in Table 7, which shows that FRA has a highly significant negative coefficient (-0.083). Notable effects are also seen in other variables. The coefficient for economic growth (ECG) in Table 6 is slightly negative but significant (-0.0007), indicating a slight positive influence on CMR. The positive coefficient for FDI in Tables 6 and 7 (0.002 and 0.005 , respectively), may suggest that certain investment kinds are not in line with the objectives of CMR. With a small but significant positive coefficient (0.0004 in Table 6 and 0.0006 in Table 7), BSD may play a mixed role in promoting CMR depending on the sectors it finances. VOA continuously exhibits significant negative coefficients (-0.005 in Table 6 and -0.053 in Table 7), highlighting the vital role that participatory policies and good governance play in boosting resilience. These results are supported by the robustness analysis in Table 8. It further supports the significance of REA (-0.003) and FRA (-0.003) in reducing CVN by confirming their substantial detrimental effects on CMR.

5. Discussion

To achieve the objective of the study, the analysis was conducted on South Asian economies by using CS-ARDL and FMOLS models. The findings infer that both REA and FRA (forest area) negatively affect the CVN, thereby enhancing CMR. These relationships can be described as REA being essential to lowering CVN and increasing CMR. CVN decreases as the proportion of renewable energy in the energy mix rises. The capacity of renewable energy sources such as solar wind and hydropower to lower greenhouse gas emissions and reliance on

Table 6. Effect of renewable energy adoption (REA) on climate vulnerability index (CMR)

Variable	CMR as a dependent CS-ARDL			
	Coefficient	Std. error	t-statistic	Probability
<i>Long-run equation</i>				
REA	-0.001^a	0.0001	-12.220	0.000
ECG	-0.0007^a	0.0003	-2.325	0.021
FDI	0.002^c	0.001	1.783	0.076
BSD	0.0004^a	0.0001	3.340	0.001
VOA	-0.005^c	0.003	-1.649	0.101
<i>Short-run equation</i>				
COINTEQ01	-0.305^a	0.1285	-2.380	0.018
D(REA)	0.0005	0.0008	0.625	0.532
D(ECG)	0.0001^a	0.0007	2.473	0.014
D(FDI)	0.0001	0.001	0.081	0.935
D(BSD)	-0.0001	0.009	-1.306	0.193
D(VOA)	-0.002	0.002	-1.020	0.309
C	-0.002	0.004	-0.446	0.656

Note(s): ^a, ^b and ^c show the significance at 1, 5 and 10% levels, respectively. Acronyms of variables are mentioned in Table 1

Source(s): Authors' own creation

Table 7. Effect of forest area (FRA) on climate vulnerability index (CVN)

Variable	Coefficient	CMR as a dependent CS-ARDL		
		Std. error	t-statistic	Probability
<i>Long-run equation</i>				
FRA	-0.083 ^a	0.021	-4.721	0.000
ECG	0.0003	0.0004	0.742	0.458
FDI	0.005 ^a	0.0009	5.506	0.000
BSD	0.0006 ^a	0.0001	4.882	0.000
VOA	-0.053 ^a	0.003	-14.169	0.000
<i>Short-run equation</i>				
COINTEQ01	-0.001 ^a	0.0004	-2.761	0.006
D(FRA)	0.0005	0.0004	1.461	0.145
D(ECG)	0.003 ^a	0.0006	5.992	0.000
D(FDI)	0.0005 ^a	0.0002	2.297	0.022
D(BSD)	-0.044 ^a	0.005	-8.472	0.000
D(VOA)	-0.001	0.001	-1.020	0.309
C	-0.002	0.002	-1.446	0.656

Note(s): ^a, ^b and ^c show the significance at 1, 5 and 10% levels, respectively. Acronyms of variables are mentioned in [Table 1](#)

Source(s): Authors' own creation

fossil fuels is what accounts for this relationship (Ibrahim *et al.*, 2022). Renewable energy directly helps stabilize environmental conditions, lessen extreme weather events, and limit the negative effects of climate variability by reducing the main drivers of climate change. Furthermore, by bolstering renewable energy technologies, which are frequently decentralized and improve energy security, REA offers communities more dependable energy options during climate-related disruptions (Chien, 2022). Similarly, FRA mitigates the CVN that greatly enhances CMR. This relationship can be described as large volumes of carbon dioxide absorbed

Table 8. Robustness analysis – effect of REA and FRA on climate vulnerability index (CMR)

Variable	CMR as a dependent Fully modified ordinary least square (FMOLS)			
	(1)		(2)	
	Coefficient	Probability	Coefficients	Probability
REA	-0.003 ^a	0.012	—	—
FRA	—	—	-0.003 ^a	0.023
ECG	0.039	0.859	-0.001 ^a	0.024
FDI	0.002 ^a	0.003	-0.0001	0.938
BSD	-0.0002	0.113	0.0006 ^a	0.001
VOA	-0.004 ^a	0.029	-0.010 ^a	0.025
Adjusted R-squared		0.484	0.439	
SE of regression		0.011	0.012	
Long-run variance		0.000	0.000	

Note(s): ^a, ^b and ^c show the significance at 1, 5 and 10% levels, respectively. Acronyms of variables are mentioned in [Table 1](#)

Source(s): Authors' own creation

by forests, which serve as natural carbon sinks and aid in controlling global temperatures. FRA and CVN have a negative relationship, which highlights how important forests are in lowering the risks brought on by climate change (Gustavsson *et al.*, 2021; Kennedy and Linnenluecke, 2022).

In addition to sequestering carbon, forests also act as buffers against floods and storms, preserve water cycles and lessen soil erosion. The stability and resilience of ecosystems depend on biodiversity, which is supported by an increased forest cover. Forests provide long-term benefits that assist communities in adapting to changing environmental conditions in addition to lowering immediate climate risks by improving these ecosystem services. The combined effects of FRA and REA highlight how crucial it is to incorporate forest preservation and the growth of renewable energy sources into frameworks for climate policy (Raihan and Tuspekova, 2022). Natural defenses against the effects of climate change are strengthened by policies encouraging afforestation and reforestation, while investments in renewable energy infrastructure lessen dependency on carbon-intensive energy sources. By addressing the causes and effects of CVN, these tactics work in concert to greatly improve CMR. Notably, the negative effects of both REA and FRA support the underlying alternative hypotheses (*H1* and *H2*).

For control variables, the analysis reveals the noteworthy negative (positive) effects of economic growth and VOA on CVN (CMR) and the positive (negative) effects of FDI inflow and BSD. The negative effect of economic growth can be explained as it is essential for improving CMR. The enhanced financial and technological ability of countries to reduce and adapt to climate risks is responsible for the decrease in vulnerability linked to economic growth. Governments and institutions can frequently invest in disaster preparedness measures, climate-resilient technologies and sustainable infrastructure when economic growth is higher. Furthermore, economic growth typically results in more funding for social safety nets, health care and education, all of which improve a community's capacity to endure and bounce back from climate-related hardships. Similarly, VOA, which measures how much citizens can express their concerns and engage in governance, also improves CMR. In the environment of better VOA, inclusive and successful climate policies are more likely to be implemented in societies with more robust VOA systems (Orazalin and Mahmood, 2021; Lei *et al.*, 2023). Participation from the public guarantees that policies represent regional needs and priorities, resulting in more well-thought-out and broadly embraced climate adaptation and mitigation programs. Accountability procedures also promote efficiency and transparency in climate project execution, lowering resource mismanagement and corruption. Communities are empowered to develop resilience through group efforts and well-informed decision-making, thanks to this participatory governance framework (Maso *et al.*, 2024).

However, inflows of FDI have a positive effect on CVN, suggesting that resilience may be negatively impacted. The environmental issues frequently connected to FDI in resource-intensive and polluting industries, especially in developing nations with weak environmental regulations, can be used to explain this positive relationship. Although FDI has the potential to boost the economy and advance technology, its role in increasing CVN emphasizes the significance of strict environmental regulations (Bhat and Ikram, 2025). Green FDI, which allocates funds to energy efficiency, renewable energy and other ecologically friendly industries, should be promoted by host nations to lessen this impact (Qamri *et al.*, 2025). We further observed the positive effect of BSD on CMR. This connection may result from funding initiatives and sectors that fuel climate risks and environmental deterioration, such as the extraction of fossil fuels, deforestation or industrial emissions. Climate vulnerabilities may worsen if a well-established banking industry puts short-term financial gains ahead of

long-term environmental sustainability. Promoting green finance programs in which banks lend money to projects that improve CMR, such as renewable energy, sustainable agriculture and climate adaptation infrastructure, can counteract this effect (Bakhsh *et al.*, 2024). The development of the banking sector and the beneficial contributions of FDI inflows necessitate strategic policy interventions to align their impacts with CMR goals even though economic growth and governance (through VOA) greatly reduce CVN. To lessen these negative effects, financial systems must integrate environmental criteria and promote sustainable investments.

6. Conclusion and policies

With a focus on the roles played by the adoption of renewable energy (REA), forest area (FRA) and other control variables such as ECG, FDI inflow, BSD and governance metrics such as VOA, this study provides a comprehensive analysis of the factors that contribute to CVN. The findings demonstrate that increased REA and FRA significantly reduce CVN by improving CMR. According to these findings, preserving forest ecosystems and expanding the infrastructure for renewable energy are essential strategies for lowering climate risks and advancing sustainable development. While economic growth and VOA both have the potential to boost resilience, they also have a detrimental impact on CVN. While inclusive governance guarantees that climate policies are open and just, and efficient economic growth makes it easier to invest in climate-resilient infrastructure. All these elements work together to show how important it is to support participatory governance and sustainable economic growth to address climate issues. On the other hand, the positive correlation between BSD, FDI inflows, and CVN suggests that specific policy interventions are required. Growth in the financial sector and FDI both support economic development, but their effects on the environment need to be carefully controlled. The banking industry's negative effects on CVN can be lessened by promoting green FDI and putting sustainable financing frameworks in place. All things considered, the study emphasized how institutional environmental and economic factors interact to shape CVN.

6.1 Policy implications

The empirical analysis yields many policy implications. As the analysis shows the negative effects of both REA and FRA on CMR, it is suggested that it is imperative to prioritize the investments in renewable energy infrastructure. Governments should set aside funds to develop wind, solar and other renewable energy projects, encourage private sector involvement and establish laws that are conducive to these projects. The benefits of resilience can be further increased by policies that support energy efficiency and the integration of renewable energy sources into national grids. The significance of forest conservation and reforestation programs is highlighted by the role that forest area (FRA) plays in reducing CVN. Lawmakers should enact comprehensive afforestation initiatives to repair degraded landscapes and bolster existing forest protection laws. Long-term success can be ensured by promoting sustainable forest management techniques in conjunction with local communities. Such actions are necessary to preserve biodiversity, meet more general environmental objectives and improve CMR.

It has been discovered that CVN is adversely affected by economic growth (ECG), indicating that resilience can be enhanced by promoting sustainable development. To promote growth without jeopardizing environmental sustainability, policymakers ought to prioritize inclusive economic policies. At the same time, investments in low-carbon technologies, sustainable industries and green infrastructure can lower climate risks and generate employment. The positive correlation between CVN and FDI inflows implies that not all types of investment are advantageous. To encourage environmentally conscious FDI, policymakers

should put policies in place such as tax breaks for green investments and more stringent environmental standards for international businesses. Investment flows and CMR goals can be aligned by developing frameworks to guarantee that FDI promotes sustainable development. Likewise, the positive correlation between CVN and BSD emphasizes the necessity of incorporating sustainability into financial sector policies. In addition to enforcing environmental risk assessments for lending activities, central banks and financial regulators ought to support green financing instruments such as green bonds and loans for climate-resilient projects.

Additionally, promoting financial inclusion and establishing climate risk insurance programs can improve resilience, particularly in communities that are already at risk. Last but not least, the detrimental effects of governance metrics such as VOA on CVN highlight how crucial transparent and participatory governance is. It is recommended that policymakers fortify the institutional frameworks that guarantee stakeholder participation in the development and execution of climate policies. Resilience-building initiatives can be more successful if civic engagement and resource allocation accountability are encouraged. All things considered, these policy suggestions emphasize the necessity of an integrated strategy that strikes a balance between institutional economic and environmental aspects to address CVN and accomplish long-term sustainability.

The findings of the study carry significant economic and commercial implications for policymakers and business stakeholders in developing economies. By highlighting the positive role of REA and FRA in enhancing CMR, the study supports a strategic shift toward green investments and sustainable resource management. Economically, this transition can reduce long-term climate-related damage, lower health costs associated with pollution, and foster stable, climate-resilient growth. Commercially, businesses investing in renewable energy technologies and forest-based carbon offset projects may gain competitive advantages through regulatory incentives, improved environmental reputation, and access to green finance. Moreover, enhanced CMR reduces operational risks, particularly in agriculture, energy and infrastructure sectors that are sensitive to climate shocks, thereby supporting long-term business continuity and investment confidence.

6.2 Limitations and future agenda

Despite many policy outputs, the current analysis is not without limitations. The use of aggregate data, which might not accurately reflect regional differences in CVN and resilience, is one of the main drawbacks. A nation's various regions may face distinct environmental problems that call for regional policy responses. To close this gap, analyses at the city or region level should be considered in future studies. The exclusive focus on macro-level factors such as the adoption of renewable energy, forest area and institutional quality while leaving out micro-level factors such as adaptation strategies at the household level and community-based resilience initiatives is another drawback. To give a more thorough picture of how community and individual actions contribute to CMR, future research could include micro-level data.

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