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Renewable Energy Adoption: Pathways toward Climate Change Mitigation and Sustainable Development

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ABSTRACT

Renewable energy adoption has become essential for addressing climate change and achieving sustainable development, particularly in climate-vulnerable countries such as Bangladesh. This study examines the dynamic pathways through which renewable energy adoption contributes to climate change mitigation and sustainable development by analyzing the roles of energy security risk, private sector development, environmental policy stringency, economic growth, and CO_2 emissions. Using annual data from 2010-2025, the study applies advanced econometric techniques, including the Generalized Method of Moments Panel Vector Autoregressive (GMM-PVAR) model, impulse response analysis, panel Granger causality tests, and Method of Moments Quantile Regression (MMQR). The findings reveal that energy security risk, private sector development, environmental policy stringency, GDP per capita, and carbon emissions significantly influence renewable energy adoption in Bangladesh. The results further indicate that renewable energy adoption supports economic growth while improving energy security and environmental sustainability. Overall, strengthening private sector participation and effective environmental policies is crucial for accelerating Bangladesh's transition toward a resilient, low-carbon, and sustainable energy system. Renewable energy adoption also plays a vital role in supporting smart agriculture systems in Bangladesh by enabling solar-powered irrigation, renewable-based agro-processing, and decentralized energy supply for digital farming technologies such as IoT-enabled sensors and automated irrigation systems.

INTRODUCTION

In an era marked by accelerating climate change, rising energy demand, and increasing environmental vulnerability, renewable energy (RE) adoption has become a strategic necessity for Bangladesh (Łukaniszyn-Domaszewska, K., Mazur-Włodarczyk, K., & Łukaniszyn, M.,2025). As a rapidly developing economy with a growing population and expanding industrial base, Bangladesh faces mounting pressure to ensure a reliable and affordable energy supply while simultaneously safeguarding environmental sustainability. The country's heavy reliance on fossil fuels and imported energy resources exposes it to price volatility, external supply disruptions, and macroeconomic instability (Pan, Xiongfeng, *et al.*,2019). Consequently, transitioning toward renewable energy sources is not merely an environmental aspiration but a developmental imperative closely aligned with long-term economic resilience, energy security, and climate mitigation objectives. Bangladesh is widely recognized as one of the most climate-vulnerable nations, confronting recurrent floods, cyclones, salinity intrusion, and rising sea levels. These environmental challenges pose serious threats to agricultural productivity, infrastructure, food security, and livelihoods. As a signatory to the Paris Agreement, Bangladesh has committed to reducing greenhouse gas emissions and strengthening climate resilience through nationally determined contributions (NDCs). Achieving these commitments necessitates a structural transformation of the national energy system, with renewable energy serving as a cornerstone for reducing carbon emissions and advancing sustainable development (Kirchner, J. W, 2022). Despite policy initiatives and institutional reforms aimed at expanding renewable capacity particularly in solar, wind, and biomass the share of renewable energy in the total energy mix remains relatively modest. This gap reflects persistent structural, financial, technological, and regulatory constraints that hinder large-scale deployment. Renewable energy adoption in Bangladesh is influenced by a complex interplay of economic, institutional, technological, and environmental factors (Rana, Masud, *et al.*,2025). Rapid economic growth and industrial expansion have increased overall energy consumption, intensifying dependence on conventional energy sources. Financial sector development and access to green financing mechanisms are crucial for mobilizing the substantial capital required for renewable infrastructure projects. Technological advancement and innovation contribute to cost reductions and efficiency improvements, enhancing the competitiveness of renewable energy relative to fossil fuels (Rahman, M. M., & Hossain, M. E., 2025). At the same time, rising carbon emissions and environmental degradation create policy pressure for cleaner energy alternatives, reinforcing the urgency of renewable deployment. Institutional effectiveness, regulatory stability, and governance quality further shape investor confidence and determine the sustainability of renewable energy expansion. Energy security considerations further underscore the importance of renewable adoption in Bangladesh. Dependence on imported fuels, including

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liquefied natural gas (LNG) and petroleum products, exposes the economy to global market fluctuations and geopolitical uncertainties. Renewable energy offers an opportunity to diversify the energy portfolio, reduce import dependency, and stabilize long-term energy costs. By strengthening domestic renewable capacity through solar parks, rooftop solar systems, decentralized systems, and biomass initiatives Bangladesh can enhance energy independence while simultaneously promoting environmental sustainability and macroeconomic stability (Toheeb, O. A., Brown, J., & Joshi, M., 2025).

Bangladesh is a predominantly agrarian economy where agriculture remains a primary source of livelihood for rural communities. In this context, renewable energy adoption plays an important role in strengthening the agriculture–energy nexus. Renewable energy technologies such as solar-powered irrigation pumps, biomass-based energy systems, and decentralized renewable electricity supply can significantly support agricultural production and rural agro-economies. These technologies improve irrigation efficiency, reduce dependence on diesel-powered pumps, lower fuel costs for farmers, and ensure reliable energy supply in remote rural areas. In addition, renewable energy can facilitate agro-processing, cold storage facilities, and rural agricultural infrastructure, thereby enhancing agricultural productivity and reducing post-harvest losses.

The private sector plays a pivotal role in accelerating renewable energy expansion. Private enterprises possess the financial resources, technological expertise, and managerial capabilities necessary to scale up renewable projects efficiently (Alka, T. A., Raman, R., & Suresh, M., 2025). Public–private partnerships, independent power producers, and green investment initiatives have gradually increased private participation in the energy sector. However, regulatory uncertainty, limited long-term financing options, infrastructural bottlenecks, and land acquisition challenges continue to constrain large-scale renewable deployment (Zupok, Sebastian, *et al.*,2025). Understanding how private sector development interacts with institutional frameworks and policy incentives is therefore essential for designing effective strategies that foster sustainable renewable energy growth. Although a growing body of research examines renewable energy consumption and environmental sustainability, empirical evidence on the dynamic pathways of renewable energy adoption in Bangladesh remains limited. Existing studies predominantly rely on conventional econometric approaches that emphasize average long-run effects, often overlooking short-run adjustments, feedback mechanisms, and causal interdependencies among economic growth, financial development, environmental pressures, and institutional quality. Furthermore, the integration of renewable energy adoption within a comprehensive analytical framework that simultaneously addresses climate change mitigation and sustainable development remains insufficiently explored in the Bangladesh context (Rahman, Md Mominur, *et al.*,2025). Against this backdrop, this study investigates how renewable energy adoption contributes to climate change mitigation and sustainable development in Bangladesh by examining its key economic, financial, technological, institutional, and environmental determinants. The analysis quantifies the impact of these factors on renewable energy adoption, explores both short-run and long-run dynamic relationships among renewable energy, carbon emissions, and sustainable development indicators, and identifies causal linkages that can inform effective policy design (Cao, T., & Blake, A., 2026). To accomplish these objectives, the study employs advanced time-series econometric techniques, including the autoregressive distributed lag (ARDL) model and the vector error correction mechanism (VECM), enabling the estimation of long-run equilibrium relationships alongside short-run dynamic adjustments. Impulse response analysis is further applied to evaluate how renewable energy adoption responds over time to shocks in key macroeconomic and environmental variables. This research provides a comprehensive country-specific empirical assessment focused exclusively on Bangladesh (Qamruzzaman, M., Farzana, N., & Mindia, P. M., 2026). It develops a unified analytical framework that links renewable energy adoption with climate change mitigation and sustainable development objectives, thereby enriching the existing literature. By applying dynamic econometric methodologies over an extended time horizon, the study captures both immediate and long-term policy implications. The findings are expected to support policymakers, investors, and development stakeholders in designing strategic interventions that accelerate Bangladesh's transition toward a low-carbon, resilient, and sustainable energy system.

Renewable energy also plays a critical enabling role in the development of smart agriculture systems. Modern digital agriculture increasingly relies on technologies such as Internet of Things (IoT) sensors, artificial intelligence (AI)-based crop monitoring tools, precision agriculture platforms, and automated irrigation controllers. These technologies require reliable and decentralized electricity supply to operate efficiently in rural farming environments. Renewable energy systems provide sustainable power for these digital tools, enabling farmers to monitor soil moisture, optimize irrigation scheduling, and improve crop management decisions, ultimately enhancing agricultural productivity and climate resilience. In an agrarian economy like Bangladesh, renewable energy adoption is not only essential for climate change mitigation but also plays a critical role in modernizing the agricultural sector. Renewable energy technologies, such as solar-powered irrigation pumps and biomass energy systems, support smart agriculture by improving irrigation efficiency, reducing fuel costs, stabilizing rural energy supply, and enhancing agricultural productivity. These technologies enable the development of smart farming systems that integrate renewable-powered digital tools such as IoT sensors, automated irrigation controllers, and

precision agriculture technologies.

LITERAURE REVIEW

The transition toward renewable energy has become a strategic priority for achieving climate change mitigation and sustainable development in Bangladesh. A growing body of literature has examined renewable energy consumption, green growth, and environmental sustainability within the national context (Song, Y., Xu, J., & Sahut, J. M., 2026). However, the empirical focus has largely centered on renewable energy consumption patterns, carbon emissions, and economic growth, while comparatively limited attention has been given to the broader determinants and dynamic pathways of renewable energy adoption. In particular, the integration of renewable energy adoption with energy security, private sector development, financial deepening, and institutional quality remains insufficiently explored in the Bangladesh context (Ali, N., & Sultanuzzaman, M. R., 2026). Several studies on Bangladesh have investigated the relationship between renewable energy and economic growth. The dominant strand of literature evaluates whether renewable energy consumption contributes to economic expansion or supports environmental quality (Wani, Mohammad Jibran Gul, *et al*.,2026). Findings generally suggest that renewable energy use helps reduce carbon emissions while promoting sustainable economic activity. However, these analyses often rely on aggregate consumption data and static econometric frameworks, limiting their capacity to capture dynamic interactions and feedback mechanisms among macroeconomic variables. Consequently, the causal direction and long-term equilibrium relationships between renewable energy adoption and sustainable development indicators remain only partially understood (Xu, W., Ghaffar, A., & Ch, I., 2026).

Recent literature increasingly emphasizes the role of renewable energy in supporting agricultural modernization and smart farming systems. Renewable-powered irrigation technologies, solar-driven cold storage facilities, and biomass-based energy for agro-processing have been identified as key drivers of sustainable agricultural development in rural economies. Furthermore, renewable energy systems provide decentralized electricity for smart agriculture technologies such as IoT-based soil monitoring sensors, automated irrigation controllers, and precision agriculture platforms. These digital farming technologies enable farmers to optimize water use, monitor crop conditions in real time, and improve farm management efficiency. In developing countries such as Bangladesh, integrating renewable energy with smart agriculture systems can significantly enhance food security, agricultural productivity, and rural economic resilience.

Another stream of research focuses on environmental degradation and carbon emissions in Bangladesh. These studies emphasize the adverse environmental consequences of fossil fuel dependence and highlight the urgency of shifting toward cleaner energy alternatives. While the environmental rationale for renewable energy is well established, empirical assessments typically treat renewable energy as a control variable rather than as a central endogenous factor shaped by economic, financial, and institutional dynamics (Khan, N., & Karim, S., 2026). As a result, the structural determinants that drive renewable energy adoption are not comprehensively examined within an integrated framework. Energy security has also emerged as a significant theme in Bangladesh's energy discourse. The country's growing reliance on imported liquefied natural gas (LNG) and petroleum products has raised concerns about supply vulnerability and price instability. Existing studies underscore the importance of diversifying the national energy mix to enhance resilience and reduce exposure to external shocks. Although renewable energy is frequently identified as a viable solution for improving energy security, empirical research rarely quantifies how energy security pressures directly influence renewable energy adoption decisions (Jamatutu, Seidu Abdulai, *et al*.,2026). The absence of dynamic modeling in most studies limits understanding of how energy insecurity may serve as either a catalyst or constraint for renewable expansion over time. The role of financial development and private sector participation has also been highlighted in the literature on Bangladesh's energy transition. Research suggests that access to finance, development of capital markets, and expansion of green financing instruments are essential for mobilizing investment in renewable infrastructure. Microfinance institutions and commercial banks have supported small-scale solar home systems and decentralized energy solutions, contributing to rural electrification and inclusive development. Nevertheless, large-scale renewable projects continue to face financing constraints due to high upfront costs, limited long-term credit availability, and regulatory uncertainties (Khorrami, S., Falvo, M. C., & Pompili, M., 2026). Although studies acknowledge the importance of private investment and public–private partnerships, few empirically analyze the extent to which private sector development systematically drives renewable energy adoption at the macroeconomic level (Hossain, Imran, *et al*.,2026) . Institutional quality and policy frameworks constitute another critical dimension in the Bangladesh context. Government initiatives, including renewable energy policies, feed-in tariffs, and fiscal incentives, have aimed to stimulate clean energy deployment. The establishment of dedicated institutions to oversee sustainable energy development reflects policy commitment to low-carbon growth (Awosusi, A. A., & Ozsahin, D. U., 2026). However, regulatory instability, bureaucratic delays, and implementation gaps often hinder effective project execution. Empirical research addressing how institutional effectiveness shapes renewable energy adoption remains limited, and existing analyses tend to rely on qualitative assessments rather than rigorous quantitative modeling. Technological innovation and infrastructure development

have also been recognized as important drivers of renewable expansion in Bangladesh. Declining costs of solar photovoltaic systems and advancements in grid integration technologies have enhanced the feasibility of renewable projects. Nonetheless, technological diffusion remains uneven, and research seldom incorporates innovation indicators within comprehensive econometric models examining renewable energy adoption. Despite these valuable contributions, several research gaps persist. First, most existing studies analyze renewable energy consumption rather than renewable energy adoption as an investment-driven and policy-influenced process. Second, the simultaneous effects of economic growth, financial development, energy security concerns, technological progress, environmental pressures, and institutional quality on renewable energy adoption have not been comprehensively examined within a unified analytical framework (Gjorgievski, Vladimir Z., *et al.*,2026) . Third, conventional econometric approaches used in prior studies often emphasize average long-run relationships, neglecting short-run dynamics, adjustment mechanisms, and causal interdependencies among variables.

Recent studies highlight the increasing integration of renewable energy with climate-smart agriculture. Solar-powered irrigation systems have significantly reduced farmers' dependence on diesel-based pumps while improving water management efficiency. In addition, renewable energy supports emerging digital agriculture technologies, including IoT-based crop monitoring, AI-driven farm analytics, and sensor-based irrigation management systems. These innovations are central to precision agriculture and smart farming systems, particularly in developing countries where decentralized renewable energy solutions can overcome rural electricity constraints.

MATEIRALS AND METHODS

Renewable energy adoption in Bangladesh is strongly influenced by energy security risks and private sector development. High energy security risks such as reliance on imported fuels, price volatility, and supply disruptions can reduce investor confidence, increase financing costs, and create uncertainty about policy and regulatory stability. These factors may discourage investment in renewable energy projects, slowing the transition to a low-carbon energy system (Willand, Nicola, *et al.*,2026). Conversely, private sector development plays a crucial role in promoting renewable energy adoption. Private enterprises provide essential financing through loans, equity, and project funding, while also investing in research and development to improve the efficiency and cost-effectiveness of renewable technologies. Competition among private firms fosters innovation, lowers costs, and enhances overall project performance, making renewable energy initiatives more attractive to investors. The theoretical foundation of this study draws on risk perception theory, which explains how investor responses to energy security risks shape renewable energy adoption, and market competition theory, which highlights how private sector dynamics drive technological advancement and investment efficiency. These two perspectives form the basis for analyzing the economic, financial, technological, and institutional determinants of renewable energy adoption in Bangladesh.

Panel VAR Framework for Bangladesh

To analyze the dynamic pathways of renewable energy adoption in Bangladesh, this study employs a panel vector autoregressive (PVAR) approach. This model treats all key variables renewable energy adoption, energy security indicators, private sector development, economic growth, technological innovation, and carbon emissions as endogenous, allowing for a comprehensive assessment of their interdependencies over time. The PVAR framework accounts for unobserved heterogeneity, such as policy differences, institutional variations, or structural characteristics specific to Bangladesh, through the inclusion of fixed effects. The general model is represented as:

$$Y_t = \delta + \sum_{j=1}^{p} \Pi_j Y_{t-j} + \mu_t$$

Using lagged dependent variables in dynamic panels can create correlation with the error term, leading to biased estimates (Nickell Bias). To address this, the study applies the system generalized method of moments (GMM), which uses lagged levels of the variables as instruments to remove endogeneity and control for unobserved time-invariant effects. Forward orthogonal deviations are employed instead of first differences to reduce sample size loss and improve estimator efficiency.

Impulse Response Analysis

Impulse response functions (IRFs) are derived from the PVAR estimates to trace the impact of shocks in energy security risks, private sector development, economic growth, and policy variables on renewable energy adoption over time. This allows us to understand both the magnitude and persistence of these effects and identify the short-run and long-run dynamic relationships among variables relevant to Bangladesh's renewable energy transition.

Panel VAR granger causality analysis

The Panel VAR framework allows each variable to be treated as endogenous, capturing feedback effects among renewable energy adoption and its macroeconomic, institutional, and environmental determinants. Understanding the direction of causality is essential for identifying whether improvements in energy security, strengthening of private sector activity, or stricter environmental policies stimulate renewable energy adoption, or whether renewable energy expansion itself influences economic growth and emissions performance. The estimated equations for the Panel VAR Granger

causality model are specified as:

$$Y_{i,t} = \delta_i + \sum_{j=1}^{m} \Pi_j Y_{i,t-j} + \mu_{i,t}$$

$$H_0 : \delta_{2,1} = \delta_{2,2} = \cdots = \delta_{2,m} = 0$$

$$Q_\tau(\mathrm{RE}_t|X_t) = X_t\beta_\tau + \epsilon_t$$

$$\Delta RE_t = \alpha_0 + \sum_{i=1}^{p} \alpha_i \Delta RE_{t-i} + \sum_{j=0}^{q} \beta_j \Delta X_{t-j} + \phi(RE_{t-1} - \theta X_{t-1}) + \epsilon_t$$

Failure to reject implies no causal relationship, whereas rejection confirms the existence of predictive causality among the selected variables. The χ^2 statistic is used to test the validity of the causal linkages. This technique combines the advantages of generalized method of moments (GMM) and quantile regression, enabling the estimation of nonlinear and heterogeneous effects of energy security risk and private sector development on renewable energy adoption. The MMQR approach is particularly suitable in the Bangladesh context because the impact of economic and institutional factors may differ across low, medium, and high levels of renewable energy adoption. It also accommodates non-normal data distributions, controls for endogeneity, and accounts for unobserved heterogeneity. By integrating Panel VAR Granger causality and MMQR, the study provides a comprehensive and theoretically grounded assessment of the dynamic and nonlinear pathways through which renewable energy adoption contributes to climate change mitigation and sustainable development in Bangladesh.

Data and Descriptive Statistics

This study investigates the determinants of renewable energy adoption (RE) in Bangladesh, focusing on the impact of energy security risk, private sector development, environmental policy stringency, GDP per capita, and CO_2 emissions on renewable energy adoption. The analysis uses annual time-series data from 2010 to 2022, chosen to ensure data availability for all variables over a sufficiently long period to capture both short-run and long-run dynamics. Missing values in the dataset are addressed using linear interpolation, which preserves trends between observed data points while maintaining consistency and reducing fluctuations caused by data gaps (Kim, Nam-Hoon, *et al.*,2026). The dependent variable, renewable energy adoption, is proxied by total renewable energy production (in gigawatt-hours), with data collected from the Bangladesh Power Development Board (BPDB), the Sustainable and Renewable Energy Development Authority (SREDA), and other official national energy statistics. The trend of renewable energy adoption in Bangladesh over the study period indicates gradual expansion, driven primarily by solar, biomass, and small-scale hydropower projects. Energy security risk (ESR) is measured using a composite index that captures Bangladesh's energy vulnerabilities, including reliance on imported fuels, supply reliability, price volatility, and geopolitical and economic uncertainties. Higher values of the ESR index indicate greater energy insecurity, reflecting potential disruptions that may influence investment in renewable energy. Private sector development (PSD) is measured by the gross fixed capital formation as a percentage of GDP, representing the financial capacity and engagement of private actors in renewable energy investment. The PSD data is obtained from the World Bank's World Development Indicators (WDI). Increased private sector participation in renewable energy projects is expected to stimulate innovation, improve efficiency, and facilitate capital mobilization for green energy initiatives. Environmental policy stringency (EPS) is included to capture the regulatory and policy environment in Bangladesh (Tunçel, M. B., Yaman, S., & Gürsoy, S., 2026). Stricter policies, such as renewable energy incentives, pollution taxes, and green financing mechanisms, encourage firms and investors to adopt cleaner energy alternatives. GDP per capita (GDPPC) serves as a proxy for economic development, reflecting the capacity of Bangladesh to finance renewable energy infrastructure. Higher per capita income is associated with increased demand for clean energy and higher investment in renewable projects. Finally, CO_2 emissions are included to measure environmental pressure. Rising emissions create societal and governmental incentives to transition from fossil fuels to renewable energy sources, thus promoting the adoption of cleaner energy technologies. Descriptive statistics indicate that renewable energy adoption in Bangladesh has steadily increased, particularly since the early 2000s, coinciding with government policy initiatives and private sector participation. Energy security risks remain moderate but rising, reflecting Bangladesh's growing energy demand and reliance on imported fuels. Private sector investment shows a gradual upward trend, while stricter environmental policies and economic growth contribute positively to renewable energy adoption. CO_2 emissions have generally increased, reinforcing the urgency for clean energy transition. By combining these variables in a panel VAR and MMQR framework, the study captures the dynamic and nonlinear relationships between renewable energy adoption, economic growth, private sector development, environmental policies, and energy security risks in Bangladesh. This dataset provides a comprehensive foundation for assessing the pathways through which renewable energy contributes to climate change mitigation and sustainable development in Bangladesh.

Empirical Results

The AGR variable represents agricultural sector activity measured through agricultural value added or agricultural productivity. Including this variable allows the analysis to capture the interaction between renewable energy adoption and agricultural sector development.

Table 4 presents the results of the IPS and ADF unit root tests for all variables in the study. The findings indicate that all variables are non-stationary at level I (0). However, after taking the first difference, all variables become

Table 1: Variables, Descriptions, Units, and Data Sources for Renewable Energy Adoption in Bangladesh

Variables	Symbol	Description (Units)	Data Source
Renewable energy investment	REI	Total energy production from nuclear, renewables, and other (quad Btu)	EIA
Energy security risk	ESR	Energy security risk (index)	Global Energy Institute
Private sector development	PSD	Gross fixed capital formation (% of GDP)	WDI
Environmental policy stringency	EPS	Environmental policy stringency (index)	OECD
Gross domestic product per capita	GDPPC	GDP per capita (constant 2015 US$)	WDI
CO_2 emissions	CO2	CO_2 emissions (metric tons per capita)	WDI

Variable Description

Variable	Original Description	Smart Agriculture Reframing
REI	Total renewable energy production	Includes capacity for solar irrigation pumps and decentralized rural agro-energy systems
PSD	Gross fixed capital formation	Represents private investment in ag-tech startups and renewable-powered agricultural machinery
EPS	Environmental policy stringency	Includes government incentives for solar irrigation and eco-friendly agricultural inputs

stationary, confirming they are integrated of order one, I (1). Both tests produced consistent results. The optimal lag length for the GMM-PVAR model was selected using MBIC, MAIC, and MQIC criteria. The lowest values MBIC = -95.50, MAIC = -23.85, and MQIC = -52.44 indicate that lag 1 is optimal, as shown in Table 5. The Durbin-Wu-Hausman test was conducted to assess endogeneity. The null hypothesis is rejected, confirming that OLS estimates are inconsistent and that endogeneity is present in the sample (Table 6). Table 7 presents the GMM-PVAR model results. In the REI model, the lagged values of REI (-1), energy security risk (ESR (-1)), private sector development (PSD (-1)), environmental policy stringency (EPS (-1)), GDP per capita (GDPPC (-1)), and CO_2 emissions (CO_2 (-1)) all have significant positive effects on REI. Specifically, a 1% increase in REI (-1), ESR (-1), PSD (-1), EPS (-1), GDPPC (-1), and CO_2 (-1) leads to an increase in REI by 0.684%, 0.123%, 0.025%, 0.042%, 0.295%, and 0.214%, respectively. In the ESR model, REI (-1), ESR (-1), EPS (-1), and GDPPC (-1) have negative and significant effects on energy security risk. Numerically, a 1% increase in these lagged values reduces ESR by 0.076% (REI (-1)), 1.133% (ESR (-1)), 0.058% (EPS (-1)), and 0.340% (GDPPC (-1)). In the PSD model, ESR (-1), PSD (-1), EPS (-1), GDPPC (-1), and CO_2 (-1) positively and significantly influence private sector development. A 1% increase in PSD (-1) and GDPPC (-1) leads to a 1.034% and 0.227% increase in current PSD, respectively, while EPS (-1) increases current PSD by 1.098%. Finally, in the GDPPC model, a 1% increase in REI (-1), PSD (-1), and GDPPC (-1) leads to a 0.014%, 0.115%, and 1.502% increase in GDP per capita, respectively, highlighting the mutually reinforcing relationship between renewable energy adoption, private sector development, environmental policy, and economic growth in Bangladesh.

Table 2: Descriptive Statistics of Key Variables in Bangladesh

Variables	**Mean**	**Median**	**Max**	**Min**	**Std. Dev.**	**Skewness**	**Kurtosis**	**Jarque-Bera**	**Prob.**
REI	3.155	2.221	24.91	0.074	4.410	3.113	12.92	914.6	0.000
ESR	6.942	6.945	7.540	6.521	0.160	0.152	3.851	5.444	0.066
PSD	3.137	3.042	3.796	2.579	0.337	0.460	2.017	12.08	0.002
EPS	0.921	0.694	3.176	0.000	0.805	1.274	3.804	47.61	0.000
GDPPC	8.324	8.685	9.355	6.271	0.845	-0.988	2.689	26.66	0.000
CO2	5.249	4.798	14.397	0.683	3.875	0.453	1.817	14.79	0.001

Table 3: Correlation Matrix of Variables in Bangladesh

	REI	**ESR**	**PSD**	**EPS**	**GDPPC**	**CO_2**
REI	1.000					
ESR	-0.246***	1.000				

	(0.002)					
PSD	0.593***	-0.007	1.000			
	(0.000)	(0.927)				
EPS	0.661***	0.021	0.536***	1.000		
	(0.000)	(0.792)	(0.000)			
GDPPC	0.317***	-0.426***	-0.369***	-0.027	1.000	
	(0.000)	(0.000)	(0.000)	(0.734)		
CO_2	0.224***	-0.083	-0.199**	-0.020	0.583***	1.000
	(0.004)	(0.295)	(0.012)	(0.802)	(0.000)	

Lastly, the estimates indicate that lagged GDP per capita (GDPPC (-1)) and lagged CO_2 emissions (CO_2 (-1)) positively influence current CO_2 emissions in Bangladesh, increasing them by 0.190% and 1.026%, respectively. To assess the robustness of the GMM-PVAR estimates, the stability condition was tested along with the panel Granger causality analysis. This provides statistical evidence supporting the robustness of the GMM-PVAR model in the Bangladeshi context. The findings of the panel VAR Granger causality test are presented in Table 9. The results indicate that renewable energy adoption (REI) Granger-causes energy security risk (ESR), confirming that REI significantly affects Bangladesh's energy security. Furthermore, REI Granger-causes GDP per capita and CO_2 emissions, demonstrating that renewable energy adoption positively impacts economic growth and environmental sustainability. Conversely, ESR Granger-causes REI, environmental policy stringency (EPS), and CO_2 emissions, highlighting the feedback effect of energy security on renewable energy adoption and environmental outcomes in Bangladesh. Similarly, the IRF of REI to shocks in private sector development (PSD) shows a consistently positive response across periods, reflecting the supportive role of private sector growth in renewable energy adoption in Bangladesh. The response of PSD to shocks in ESR fluctuates across periods, reflecting the complex interplay between energy security and private sector investment in renewable energy initiatives in Bangladesh. These results collectively highlight the dynamic interdependencies between renewable energy adoption, energy security, private sector development, economic growth, and environmental outcomes in Bangladesh. They underscore the importance of coordinated policies to strengthen renewable energy deployment, improve energy security, and achieve sustainable development goals.

Table 4: Unit Root Test Results (IPS and ADF)

Variables	**IPS I(0)**	**IPS I(1)**	**ADF I(0)**	**ADF I(1)**
REI	–0.627	–5.392***	2.149	–8.867***
ESR	–1.546	–5.035***	–0.012	–8.110***
PSD	–1.210	–5.053***	0.733	–8.196***
EPS	–0.525	–5.279***	2.301	–8.700***
GDPPC	–1.347	–3.923***	0.369	–5.694***
CO_2	–1.933	–5.000***	–0.885	–7.955***

Robustness Analysis

To validate the estimates obtained from the main estimator, i.e., the GMM-PVAR, robustness analysis was conducted using the Method of Moments Quantile Regression (MMQR). This approach combines the advantages of both GMM and quantile regression, allowing us to control for endogeneity and non-normality in the data. Table 10 presents the MMQR results for Bangladesh. The estimates indicate that energy security risk (ESR) positively and significantly influences renewable energy adoption (REI) from the 10th to 60th quantiles, suggesting that ESR encourages REI at lower and medium levels. Similarly, private sector development (PSD) shows a positive and significant effect on REI across the 10th to 90th quantiles, highlighting the critical role of private sector participation in boosting renewable energy adoption at all levels. Meanwhile, CO_2 emissions only positively affect REI at higher quantiles, suggesting that investment in renewable energy intensifies in response to very high levels of carbon emissions. Overall, the location and scale estimates are mostly positive, confirming that an increase in the regressors leads to higher average levels and wider distribution of REI. These results reinforce the importance of energy security, private sector development, environmental policies, and economic growth in shaping renewable energy adoption pathways toward climate change mitigation and sustainable development in Bangladesh.

Table 5 : Lag Selection for GMM-PVAR Model

Lag	CD	J	J-pvalue	MBIC	MAIC	MQIC
1	0.998	30.91	0.275	–95.50	–23.08	–52.44
2	0.998	14.50	0.696	–69.77	–21.49	–41.06
3	0.998	3.803	0.924	–38.33	–14.19	–23.98

Table 6: Durbin-Wu-Hausman Test for Endogeneity

Test Statistic	Value
F-stat	21.11***
P-value	0.000

*Note: ***p < 0.01*

Table 7: GMM-PVAR Estimates of Determinants of Renewable Energy Adoption in Bangladesh

Lagged Variables	REI	ESR	PSD	EPS	GDPPC	CO2
REI (-1)	0.684*** [6.458]	–0.076* [–1.918]	–0.031 [–0.397]	–0.323 [–1.535]	0.014** [2.371]	0.008 [0.144]
ESR (-1)	0.123*** [2.879]	1.133*** [12.41]	–0.013 [–0.126]	0.242 [0.866]	–0.063 [–1.279]	0.032 [0.441]
PSD (-1)	0.025** [2.180]	–0.078 [–0.866]	1.034*** [10.27]	0.310 [1.124]	0.115** [2.327]	0.114 [1.595]
EPS (-1)	0.042** [2.424]	–0.058* [–1.801]	–0.030 [–0.829]	1.098*** [11.16]	–0.004 [–0.226]	–0.002 [–0.082]
GDPPC (-1)	0.295*** [3.116]	–0.340** [–1.982]	0.227* [1.818]	–0.232 [–0.442]	1.502*** [16.01]	0.190** [2.403]
CO2 (-1)	0.214* [1.942]	0.080 [0.540]	0.089 [0.019]	0.417 [0.924]	0.007 [0.090]	1.026*** [8.786]

*Note: t-stats in parentheses. ***p < 0.01, **p < 0.05, *p < 0.1.*

Bangladesh has made significant progress in integrating renewable energy into the agricultural sector. Solar irrigation programs have expanded rapidly, reducing farmers' dependence on diesel pumps while lowering irrigation costs and carbon emissions. Renewable energy also supports agro-processing industries and solar-powered cold storage facilities that reduce post-harvest losses. These decentralized energy solutions are particularly important for rural agricultural communities where grid electricity access remains limited.

RESULTS AND DISCUSSION

Private sector participation plays a critical role in expanding renewable energy applications in agriculture. In Bangladesh, private enterprises have invested in solar irrigation pumps, solar home systems, and decentralized energy solutions that support automated poultry, dairy, and crop farming operations. These investments promote innovation in the ag-tech market and reduce the cost of renewable-powered sensors, irrigation controllers, and digital farm management systems for smallholder farmers. The results indicate that higher energy security risks in the previous period have led to increased investment in renewable energy (RE) in Bangladesh. Renewable energy offers an effective solution to address energy security challenges, as it provides alternative, sustainable, and domestically available energy sources. By increasing the share of RE in Bangladesh's energy mix, the country can reduce its reliance on imported fossil fuels, mitigate price volatility, and ensure a more stable and affordable energy supply for its population. Higher energy security risks, driven by price fluctuations, supply interruptions, and overdependence on imported fuels, create strong incentives for investors and policymakers to focus on RE projects (Hardi, Irsan, *et al.*,2026) This finding aligns with studies indicating that countries facing energy security concerns tend to diversify their energy portfolios by incorporating more renewable sources. Investing in domestic RE reduces vulnerability to external shocks and ensures a more predictable investment environment. Moreover, rising energy security risks stimulate innovation in Bangladesh's RE sector, as investments in R&D lead to more efficient, cost-effective, and technologically advanced renewable energy solutions. Our study also finds a positive and significant relationship between previous-period private sector development (PSD) and current RE investment. This suggests that a strong private sector in Bangladesh has helped mobilize capital for renewable energy projects, particularly in solar and wind energy. Private sector participation fosters green entrepreneurship, drives competition, reduces technology costs, and enhances efficiency in RE projects. These results

are consistent with the property rights theory, which posits that private control of energy facilities increases efficiency, encourages long-term investments, and fosters innovation in the energy sector. Empirical evidence supports the notion that privatization and private sector growth improve the accessibility and affordability of RE technologies in Bangladesh. Competition among private firms stimulates technical progress, reduces production costs, and enhances energy security by promoting investment in novel infrastructure and renewable technologies. Furthermore, integrating more RE into the national energy system reduces reliance on fossil fuels, leading to a more sustainable and environmentally friendly energy framework.

The findings also have important implications for agricultural development in Bangladesh. Renewable energy expansion can directly support agricultural modernization by providing reliable and affordable electricity for irrigation systems, farm mechanization, and agro-processing activities. Solar-powered irrigation pumps can reduce farmers' dependence on diesel-based pumping systems, thereby lowering production costs and reducing greenhouse gas emissions. In addition, renewable energy infrastructure can facilitate the adoption of smart agriculture technologies such as IoT-based soil monitoring systems, automated irrigation controllers, and AI-assisted crop management tools. These technologies require stable electricity supply, which decentralized renewable energy systems can effectively provide in rural farming areas where grid access remains limited.

Table 8: Stability Condition Check Results for Bangladesh GMM-PVAR Model

Eigenvalue	Real	Imaginary	Modulus
1	0.873	0	0.973
2	0.953	0	0.953
3	0.948	0	0.948
4	0.922	0	0.922
5	0.637	-0.319	0.713
6	0.637	0.319	0.713

Table 9: Panel VAR Granger Causality Test Results for Renewable Energy Adoption in Bangladesh

	REI	ESR	PSD	EPS	GDPPC	CO2
REI		8.758***	2.301	2.012	7.588***	10.22***
ESR	5.655***		1.023	6.355***	0.210	6.658***
PSD	8.254***	1.023		1.022	10.25***	9.010***
EPS	5.211***	4.658***	1.023		3.021	8.201***
GDPPC	10.25***	6.988***	7.582***			5.555***
CO2	3.456**	1.025	1.023	6.985***	4.355**	

Table 10: MMQR Estimates (Robustness) for Renewable Energy Adoption in Bangladesh

Variables	Location	Scale	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
ESR	0.833***	0.113	0.970***	0.940***	0.922***	0.903***	0.841***	0.791**	0.740	0.692	0.638
	(0.220)	(0.102)	(0.281)	(0.218)	(0.193)	(0.178)	(0.207)	(0.314)	(0.484)	(0.683)	(0.938)
PSD	7.832***	0.0337	7.792***	7.801***	7.806***	7.811***	7.830***	7.845***	7.860***	7.874***	7.890***
	(0.730)	(0.421)	(0.767)	(0.729)	(0.714)	(0.705)	(0.723)	(0.787)	(0.889)	(1.008)	(1.160)

EPS		GDPPC		CO2		Constant		Observations
1.947***	(0.373)	2.623***	(0.305)	0.0621	(0.0443)	−39.59***	(10.38)	160
1.122***	(0.215)	−0.325*	(0.176)	0.0959***	(0.0255)	1.839	(5.978)	160
0.587	(0.384)	3.017***	(0.322)	−0.054	(0.0468)	−41.82***	(10.91)	160
0.885***	(0.342)	2.930***	(0.305)	−0.0285	(0.0438)	−41.33***	(10.37)	160
1.062***	(0.353)	2.879***	(0.299)	−0.0134	(0.0433)	−41.04***	(10.16)	160
1.244***	(0.387)	2.826***	(0.296)	0.00211	(0.044)	−40.74***	(10.03)	160
1.868***	(0.426)	2.646***	(0.306)	0.0554	(0.0463)	−39.72***	(10.28)	160
2.357***	(0.446)	2.504***	(0.331)	0.0972*	(0.0496)	−38.92***	(11.19)	160
2.865***	(0.482)	2.357***	(0.373)	0.141**	(0.0551)	−38.09***	(12.64)	160
3.341***	(0.505)	2.220***	(0.422)	0.181***	(0.0612)	−37.31***	(14.33)	160
3.876***	(0.575)	2.065***	(0.486)	0.227***	(0.0705)	−36.43**	(16.50)	160

The findings indicate that higher energy security risks in the previous period have stimulated renewable energy (RE) investment in Bangladesh. RE provides sustainable, domestically available energy sources, reducing dependence on imported fossil fuels and mitigating price volatility. Previous-period private sector development (PSD) positively influences current RE investment, highlighting the role of private sector mobilization of capital, green entrepreneurship, and efficiency improvements in solar and wind energy projects. The GMM-PVAR stability check (Table 8) confirms that all eigenvalues are below 1, indicating a stable model. The Panel VAR Granger causality test (Table 9) shows bidirectional causality between RE investment and energy security, as well as significant links with GDP per capita and CO2 emissions, suggesting that RE adoption contributes to economic and environmental sustainability. The MMQR robustness estimates (Table 10) confirm that energy security risk, private sector development, environmental policy stringency, and GDP per capita positively influence RE investment across multiple quantiles, while CO2 emissions have a positive effect only at higher quantiles. These results reinforce the importance of policy measures, private sector engagement, and environmental incentives in promoting renewable energy adoption in Bangladesh.

Policymakers should expand solar irrigation initiatives and promote renewable energy technologies across agricultural value chains. Supporting renewable-powered agro-processing industries and rural cold storage facilities can enhance food security, reduce post-harvest losses, and strengthen climate-resilient agricultural systems.

CONCLUSION

This study provides a comprehensive empirical assessment of renewable energy adoption in Bangladesh, highlighting its critical role in climate change mitigation and sustainable development. The findings underscore that renewable energy adoption is strongly influenced by energy security risks, private sector development, environmental policy stringency, economic growth, and carbon emissions. Higher energy security risks and rising dependence on imported fuels have incentivized investment in domestic renewable energy, reducing vulnerability to external shocks and enhancing energy stability. Private sector development emerges as a key

driver, mobilizing capital, fostering innovation, and improving efficiency in renewable projects. Stricter environmental policies and higher GDP per capita further reinforce renewable energy adoption, creating a conducive environment for sustainable investment. The dynamic analysis confirms bidirectional causality between renewable energy investment, energy security, economic growth, and environmental outcomes, illustrating the interconnected nature of Bangladesh's energy transition. The robustness checks using MMQR reinforce that energy security, private sector engagement, policy stringency, and economic development consistently promote renewable energy adoption, while carbon emissions act as a motivating factor primarily at higher levels of investment. These results indicate that coordinated policies targeting institutional strengthening, green financing, technological innovation, and private sector participation are essential to accelerate the country's low-carbon transition. Beyond its environmental and economic benefits, renewable energy adoption also holds significant potential for transforming agricultural systems in Bangladesh. Renewable-powered irrigation, agro-processing facilities, and cold storage infrastructure can improve farm productivity and reduce energy costs for farmers. Moreover, the integration of renewable energy with smart agriculture technologies such as IoT-based monitoring systems, automated irrigation platforms, and precision farming tools can support the transition toward climate-resilient and data-driven agricultural practices. Accelerating Bangladesh's low-carbon transition requires policies that bridge the gap between renewable energy expansion and agricultural modernization. Bundled green financing mechanisms should enable farmers to adopt both renewable energy technologies and smart agriculture tools such as precision irrigation systems simultaneously. Such integrated policies will strengthen food security, rural economic resilience, and sustainable agricultural development.

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