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Energy Consumption and CO_2 Emissions in Bangladesh: Evidence from ARDL and VECM Approaches

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Abstract
This study empirically analyzes the multivariate Granger causality connection between economic growth, energy use, financial development, trade openness, and CO_2 emissions in Bangladesh using quarterly data from 1999 to 2023. The study employs the Zivot-Andrews structural break unit root test, the ARDL bounds testing approach to cointegration, OLS and ECM to assess long- and short-term impacts, the VECM Granger causality approach, and the innovative accounting approach (IAA) to verify the robustness of the causality analysis. The results indicate long-term cointegration among the variables and reveal that increased energy consumption, economic expansion, and financial sector growth tend to elevate CO_2 emissions, whereas greater trade openness appears to mitigate them. The causal analysis demonstrates a two-way relationship between energy use and carbon emissions, while the development of the financial sector is shown to Granger-cause CO_2 emissions, economic growth, and trade openness. These insights could offer new perspectives for policymakers in crafting comprehensive strategies that encompass economic, financial, trade, and environmental aspects to maintain Bangladesh's economic growth trajectory.

Keywords: Growth, Financial Development, Energy, CO_2 emissions.

Introduction
Globally, achieving economic growth without increasing carbon dioxide emissions has been a significant challenge for many nations, drawing attention to the concept of "green and low-carbon growth." A central question is whether sustained economic expansion can occur without a corresponding rise in energy consumption or greenhouse gas emissions. Developing countries contend that limiting carbon-based energy could impede their economic progress, suggesting that industrialized nations, which have historically contributed the majority of emissions, should enhance their financial support. This issue is closely linked to post-Kyoto climate negotiations,

underscoring the necessity for empirical frameworks to analyze the interplay between environmental and economic factors.

Recent studies have investigated the causal relationships among energy consumption, CO2 emissions, and economic growth, but inconsistent results highlight the need for further exploration. This research focuses on Bangladesh, the world's eighth-most populous country, where escalating energy demand poses challenges to environmental sustainability. Using quarterly data from 1980 to 2020, the study examines the interactions between economic growth, energy consumption, financial development, trade openness, and CO2 emissions. The methodology includes (i) the Zivot-Andrews structural break unit root test, (ii) the ARDL bounds testing approach for cointegration to assess long-term relationships in the presence of structural breaks, (iii) OLS and ECM to evaluate long- and short-term effects, (iv) the VECM Granger causality framework to determine directional relationships, and (v) the innovative accounting approach (IAA) to verify the robustness of causality findings.

The results confirm long-term cointegration among economic growth, energy consumption, financial development, trade openness, and CO2 emissions in Bangladesh. The study demonstrates that increased energy consumption, economic growth, and financial development elevate emissions, while greater trade openness reduces them. Causality analysis reveals bidirectional relationships between energy use and CO2 emissions. Financial development Granger-causes CO2 emissions, economic growth, and trade openness. Feedback effects are observed between trade openness and CO2 emissions, as well as between economic growth and energy use. Bidirectional causality exists between trade openness and energy consumption, while economic growth drives trade openness. These findings offer valuable insights for policymakers aiming to harmonize Bangladesh's economic, financial, trade, and environmental objectives.

Review of Literature

The initial segment of existing energy research encompasses diverse studies with mixed outcomes regarding the relationship between energy consumption and economic growth. In recent times, this energy-growth connection has been extensively examined empirically, following the pioneering work of (1). The results from contemporary energy literature are inconclusive because of the use of diverse econometric techniques, such as vector error correction modeling (VECM), unit root tests, multivariate cointegration, panel cointegration, bivariate causality tests, simple regressions, correlation analysis, and novel accounting methods to identify the causal relationship between economic growth and energy consumption (2); (3). The ambiguous empirical findings have not provided economic policy planners with sufficient guidance to develop a comprehensive energy strategy capable of supporting sustained long-term economic growth (4), (5). (6) the connection between economic growth and electricity consumption was examined using data from 74 economies, categorized into five panels (low income, lower middle income, upper middle income, and high income). Employing the panel cointegration approach, they discovered cointegration only in the high-income, and upper-middle-income countries. Understanding the causal direction between economic growth and energy consumption is crucial from both policy and theoretical perspectives (7).

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Recent research by (5) and (8) reviewed literature on the link between energy consumption and economic growth, outlining four hypotheses: (1) The growth hypothesis asserts energy consumption drives economic growth, indicating policies reducing energy use should be avoided. (2) If economic growth causes energy consumption, then energy reduction policies will not adversely affect economic growth. (3) The feedback hypothesis suggests a bidirectional causal relationship, where rising economic growth increases energy demand, fueling further economic growth. Energy conservation measures could impede economic growth. (4) The neutrality hypothesis argues that no causal relationship exists, implying that energy conservation or exploration policies would minimally impact economic growth. Another line of research explores the relationship between economic growth and CO_2 emissions, called the environmental Kuznets curve (EKC). The EKC hypothesis proposes an inverted U-shaped relationship between economic growth and CO_2 emissions, suggesting that emissions rise initially, but decline as the economy develops. Studies by (9), (10), (11), (12), and (13), have confirmed the existence of the EKC. However, (14) used panel data and found inconclusive results regarding the relationship between economic growth and CO_2 emissions. More recent studies have validated the EKC using cross-sectional data for various regions and country groups. These include (15) for ASEAN countries; (8) for Central America and Commonwealth of Independent States; (16) for BRIC countries; (17, 18) for Russia; and (19) for 138 developing and developed countries. Additionally, time series data analyses by (20), (21), (22), and (23) have also supported the empirical presence of the EKC for various countries, including Brazil, India, Malaysia, France, Pakistan, Tunisia, China, Romania, and Italy.
The third research strand focuses on individual country case studies. For example, in the United States, study (24) investigated the dynamic relationship among CO_2 emissions, income, and energy consumption. Their results demonstrated that CO_2 emissions Granger-cause income, whereas energy consumption drives CO_2 emissions. Researchers (22), and (23) conducted analogous analyses in Malaysia and France. The research results indicated that in France, economic growth is a Granger cause of energy usage and carbon emissions, whereas Malaysia demonstrates a one-way causal relationship from economic growth to energy consumption. Research conducted by (25) examined data from Tunisia to investigate causal links between energy use, income, and CO_2 emissions. The empirical results from this study indicated that energy consumption drives economic growth, which in turn leads to increased CO_2 emissions.
In India, research (26) examined causality between income and CO_2 emissions while incorporating investment and employment as additional variables, but detected no causal linkage between income and CO_2 emissions. Using Chinese data, study (27) applied multivariate causality tests to assess connections among economic growth, energy consumption, and CO_2 emissions. The analysis revealed that economic growth Granger-causes energy consumption, which in turn leads to CO_2 emissions. Research (28) identified a feedback hypothesis between economic growth and CO_2 emissions in Turkey.
For South Africa, study (29) concluded that energy consumption Granger-causes CO_2 emissions, which subsequently Granger-cause economic growth. Conversely, research (30) re-evaluated causality among energy consumption, economic growth,

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and CO_2 emissions, identifying unidirectional causality from economic growth to CO_2 emissions. Similarly, study (31) explored linkages between energy consumption, economic growth, and energy pollutants in India. Their empirical results highlighted bidirectional causality between energy consumption and CO_2 emissions, alongside a neutral hypothesis between CO_2 emissions and economic growth.

In Pakistan, (32) established a causal relationship between the variables, concluding that they were cointegrated in the long term. The ARDL bounds testing validated these long-term findings. Their VECM causality analysis demonstrated a bidirectional relationship between energy consumption and CO2 emissions, while a unidirectional causal relationship was observed from CO2 emissions to economic growth. In Greece, (6) utilized the VECM Granger causality test to investigate the causal relationships among energy intensity, income, and CO2 emissions using the Johansen multivariate cointegration approach. The results revealed a long-term connection between the variables. The VECM Granger causality analysis indicated a unidirectional causal relationship from economic growth to both energy intensity and CO2 emissions, as well as a bidirectional relationship between energy intensity and CO2 emissions. In another area of economic research, (33) examined the influence of additional potential determinants of CO2 emissions, such as economic, institutional, and financial factors. In their pioneering study, (34) analyzed the effects of economic and financial development on CO2 emissions in Brazil, Russia, India, China, the United States, and Japan. Later, (33) explored the role of institutions in CO2 emissions. Their empirical findings suggested that economic development, trade openness, financial development, and institutions contribute to environmental protection while supporting the EKC hypothesis. In the context of China, (35) contended that financial sector policies enable firms to adopt advanced technologies that reduce CO2 emissions and enhance domestic production. They also argued that financial development promotes capitalization and financial regulations that improve environmental quality. Subsequently, (36) studied the impact of economic growth, energy consumption, and financial development on carbon emissions in China.

The researchers demonstrated that energy consumption, economic growth, and trade openness adversely affect environmental quality. In contrast, financial development and foreign direct investment contribute to reducing environmental degradation (37) re-examined the finance-environment nexus, finding that financial development elevates CO2 emissions due to inefficient distribution of financial resources. In Sub-Saharan Africa, (38) investigated interactions among energy consumption, income, financial development, and CO2 emissions, including investment and employment as variables affecting production. Their results suggested energy consumption stimulates economic growth, increasing demand for financial services and promoting financial development. This development improves environmental quality by controlling CO2 emissions through effective financial regulations. However, (8) observed that financial development in Turkey failed to significantly reduce CO2 emissions. Existing literature also explores the link between international trade and environmental outcomes. (10) argued that the environmental impact of trade depends on policies adopted within an economy. Two perspectives dominate debates on trade's effect on CO2 emissions. The first posits that trade openness facilitates participation in international markets, expanding nations' market share (39). This stimulates cross-country competition, improving resource-use efficiency and promoting cleaner technologies to curb emissions. The second perspective contends that international trade accelerates natural resource depletion.

The utilization of natural resources leads to heightened CO_2 emissions and environmental degradation, as evidenced by studies such as (40), (41), (42). In Brazil, (20) established a positive link between international trade and CO_2 emissions. (21) provided support for the pollution haven hypothesis in Italy, while (28) explored the relationships between economic growth, CO_2 emissions, energy consumption, and trade openness in Turkey. The study found that trade openness boosts economic growth, whereas higher income levels increase CO2 emissions. (43) analyzed this issue across Chinese provinces and concluded that industrial development is linked to higher CO_2 emissions due to energy consumption. (44) utilized the ADF unit root test and (45) cointegration test to validate the Environmental Kuznets Curve (EKC) in Pakistan, highlighting the positive influence of trade openness on CO_2 emissions. Conversely, (39) found that trade openness reduces CO_2 emissions, while (46) reported that trade openness negatively impacts environmental quality in India. Numerous studies have investigated the connections between energy consumption, economic growth, and energy-related pollutants in Bangladesh. For example, (47) determined that economic growth Granger-causes energy consumption, a finding consistent with (48). In contrast, (49) and later (50) concluded that energy consumption drives economic growth. Additionally, (24) and (8) identified a neutral relationship between energy consumption and economic growth. (51) examined the interplay among energy consumption, economic growth, and CO2 emissions, while also considering capital and urbanization as potential factors influencing energy consumption and energy-related pollutants.

The researchers observed no long-term relationship between the variables and determined that urbanization acts as a Granger causal factor for energy consumption. Previous empirical studies have produced inconsistent results, providing policymakers with limited practical guidance to develop integrated strategies across economic, energy, financial, trade, and environmental sectors to balance economic growth and environmental sustainability in Bangladesh. This inconsistency arises from the omission of financial development and trade openness in earlier analyses of the connections among economic growth, energy consumption, and CO2 emissions. The current study aims to address this gap in energy research by focusing on Bangladesh as a representative case.

Methodological Framework and Data Acquisition

The existing body of research offers numerous empirical investigations into the dynamic interplay between economic growth, energy usage, and carbon dioxide emissions. For example, studies have been conducted by (23) in France and Malaysia; (24) in the United States; (37), (27), and (52) for China; (28) and (4) for Turkey; Pao and (17) for Brazil; and (38) for India and Bangladesh, all examining the causal connections among these factors. Additional research has incorporated other potential influencers of CO2 emissions, such as capital (53) and later (29), fossil fuel consumption (54), coal usage (55)and subsequently (46), electricity consumption (15), openness and urbanization (6), foreign direct investment (56) energy intensity (57) and later (58), and trade openness (44) and subsequently (39) for Pakistan.

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Financial development was introduced as a potential factor influencing CO2 emissions (33) and (34). Subsequently, (35), (36), and (59) explored the empirical connection between financial development and energy emissions in China. Well-developed financial markets promote capitalization by drawing domestic and foreign investors, accelerating economic growth (60). Financial development enables firms to access resources for implementing eco-friendly and energy-efficient technologies (61), (62) and produce fewer carbon emissions (33). Financial development can also have adverse effects on the environment by contributing to increased CO2 emissions through the expansion of the industrial sector. Expanding on this discussion, we explore the relationship between economic growth, energy consumption, financial development, and CO2 emissions, while also incorporating the role of trade openness. Similarly, (63) investigated the impact of trade on environmental quality. The researchers analyzed the trade model by examining composition, scale, and technological effects. Their results demonstrated that trade openness can positively influence the environment when the technological effect outweighs the combined composition and scale effects. This implies that international trade can boost the income of developing countries, motivating them to adopt cleaner production methods. (64) argued that international trade improves environmental quality through environmental regulations and capital-labor pathways. They highlighted that free trade reduces CO2 emissions by relocating pollution-intensive production from developing to developed countries. (65) found that environmental quality improves when the environmental regulatory effect exceeds the capital-labor effect. Similarly, (66) suggested that trade openness can enhance environmental quality, depending on government policies. Local governments can implement environmental regulations to reduce CO2 emissions. However, the movement of production factors may also lead to the transfer of polluting industries from developed to developing economies, where environmental regulations are often weakly enforced. For example, (67) found that trade openness has a negative impact on environmental quality in less developed countries. like Nigeria. The general form of an empirical equation is modelled as follows:

$$C_t = f\,(EC_t\,, G_t\,, FD_t\,, TR_t\,)$$

We transform all the series into logarithmic forms to obtain direct elasticity estimates. The empirical model is structured as follows:

$$lnC_t = \alpha_0 + \alpha_{EC} lnEC_t + \alpha_G lnG_t + \alpha_{FD} lnFD_t + \alpha_{TR} lnTR_t + \mu_t$$

In the equation, C_t represents per capita CO2 emissions in kilotons, EC_t denotes per capita energy consumption, G_t stands for per capita real GDP as an economic growth indicator, FD_t signifies per capita real domestic credit to the private sector as a measure of financial development, and TR_t indicates per capita trade openness. The error term μ_t was assumed to have a normal distribution with zero mean and constant variance. It is expected that higher energy consumption will lead to increased carbon emissions, with $\alpha_{EC} > 0$. If $\alpha_G > 0$, economic growth is associated with higher CO2 emissions; otherwise, a value of $\alpha_G < 0$. A well-functioning financial sector may facilitate firms' adoption of cleaner, environmentally friendly technologies (68), resulting in $\alpha_{FD} < 0$. However, if the financial sector prioritizes industrial growth, a value $\alpha_{FD} > 0$. The anticipated sign of trade openness is negative $\alpha_{TR} < 0$ if environmental regulations reduce pollutant-intensive production. Nonetheless, (10) and (28) contend that α_{TR} could be positive if the dirty industries of developing economies contribute significantly to CO2 emissions through their production processes. Data on real GDP per capita, energy consumption, domestic credit to the private sector, and trade openness (exports plus imports), were obtained from the World Development Indicators while CO2 emissions (in kilotons) data has been taken from trading economics. This study covers the period 1980–2020.

Estimation Strategy
In applied economics, researchers have access to various unit root tests to examine the stationarity characteristics of variables. These tests include the ADF by (69), P-P by (70), KPSS by (71), DF-GLS by (72), and (73). However, these tests often yield biased and misleading results due to their inability to account for structural breakpoints within the data series. To address this limitation, (74) introduced three models designed to test the stationarity of a series while accounting for a structural break point. The first model accommodates a single shift in the variables' level form, the second allows for a one-time change in the slope of the trend component (i.e., trend function), and the third integrates a simultaneous one-time change in both the intercept and the trend function of the variables used empirically. These models were applied by (74) to assess the hypothesis of a single structural break occurring within the series under analysis.

$$\Delta y_t = b + by_{t-1} + ct + cEU_t + \sum_{j=1}^{k} f_j \Delta y_{t-j} + \mu_t \dots\dots\dots (3)$$

$$\Delta y_t = j + jy_{t-1} + ht + cET_t + \sum_{j=1}^{k} f_j \Delta y_{t-j} + \mu_t \dots\dots\dots (4)$$

$$\Delta y_t = j + jy_{t-1} + ht + dEU_t + dET_t + \sum_{j=1}^{k} f_j \Delta y_{t-j} + \mu_t \dots\dots\dots (5)$$

Where the dummy variable is indicated by EU_t showing mean shift occurred at each point with time break while trend shift variables are shown by ET_t . So,

$$EU_t = \begin{cases} 1 \dots if\ t > TB \\ 0 \dots if\ t < TB \end{cases} and\ EU_t = \begin{cases} t - TB \dots if\ t > TB \\ 0 \dots if\ t < TB \end{cases}$$

The null hypothesis j=0 for the unit root break date posits that the series is non-stationary with drift and contains no structural break information. In contrast, the j=0 alternative hypothesis proposes that the variable is trend-stationary with a single unknown break in the time trend. The Zivot-Andrews unit root test evaluates all potential time points as candidates for structural breaks, performing sequential regression analyses for each possible break location. The test identifies the specific breakpoint that minimizes the one-sided t-statistic associated with testing $\hat{j}(= j - 1) = 1$. Zivot-Andrews highlight that the asymptotic distribution of the test statistics diverges to infinity near the endpoints of the sample period, requiring the exclusion of these regions. Accordingly, we applied their suggested trimming ranges of (0.16T, 0.86T) to the sample data.

The ARDL Bounds Testing Cointegration Approach

After evaluating the stationarity properties of the series, we utilized the ARDL bounds testing approach introduced by (75) to analyze the long-run relationship between economic growth, energy consumption, financial development, trade openness, and carbon emissions in Bangladesh's economy. Various cointegration techniques, such as those proposed by (76), (77), and (70), have been widely used in numerous studies to identify cointegration among variables. However, these traditional methods require all series to be integrated in the same order. The ARDL bounds testing method provides several advantages over conventional cointegration techniques, particularly its flexibility in handling the stationary properties of variables. This approach is especially effective when variables are stationary at I(1), I(0), or a mix of both. Additionally, the ARDL bounds testing method delivers reliable and consistent results for small-sample datasets, as highlighted by (78), making it well-suited for Bangladesh's context. This method allows for the simultaneous examination of both short-run and long-run dynamics. The unrestricted error correction model (UECM) form of the ARDL model is represented as follows:

$$\Delta lnC_t = \alpha_1 + \alpha_{DUM}DUM + \alpha_C lnC_{t-1} + \alpha_{EC} lnEC_{t-1} + \alpha_G lnG_{t-1} + \alpha_{FD} lnFD_{t-1} + \alpha_{TR} lnTR_{t-1} + \sum_{i=1}^{p} \alpha_i \Delta lnC_{t-1} + \sum_{j=0}^{q} \alpha_j \Delta lnEC_{t-1} + \sum_{k=0}^{r} \alpha_k \Delta lnG_{t-1} + \sum_{l=0}^{s} \alpha_l \Delta lnFD_{t-1} + \sum_{m=0}^{t} \alpha_m \Delta lnTR_{t-1} + \mu_t \dots \dots \dots (6)$$

$$\Delta lnEC_t = \alpha_1 + \alpha_{DUM}DUM + \alpha_C lnC_{t-1} + \alpha_{EC} lnEC_{t-1} + \alpha_G lnG_{t-1} + \alpha_{FD} lnFD_{t-1} + \alpha_{TR} lnTR_{t-1} + \sum_{i=1}^{p} \theta_i \Delta lnEC_{t-1} + \sum_{j=0}^{q} \theta_j \Delta lnC_{t-1} + \sum_{k=0}^{r} \theta_k \Delta lnG_{t-1} + \sum_{l=0}^{s} \theta_l \Delta lnFD_{t-1} + \sum_{m=0}^{t} \theta_m \Delta lnTR_{t-1} + \mu_t \dots \dots \dots (7)$$

$$\Delta lnG_t = \alpha_1 + \alpha_{DUM}DUM + \alpha_C lnC_{t-1} + \alpha_{EC} lnEC_{t-1} + \alpha_G lnG_{t-1} + \alpha_{FD} lnFD_{t-1} + \alpha_{TR} lnTR_{t-1} + \sum_{i=1}^{p} \emptyset_i \Delta lnG_{t-1} + \sum_{j=0}^{q} \emptyset_j \Delta lnC_{t-1} + \sum_{k=0}^{r} \emptyset_k \Delta lnEC_{t-1} + \sum_{l=0}^{s} \emptyset_l \Delta lnFD_{t-1} + \sum_{m=0}^{t} \emptyset_m \Delta lnTR_{t-1} + \mu_t \dots \dots \dots (8)$$

$$\Delta lnFD_t = \alpha_1 + \alpha_{DUM}DUM + \alpha_C lnC_{t-1} + \alpha_{EC} lnEC_{t-1} + \alpha_G lnG_{t-1} + \alpha_{FD} lnFD_{t-1} + \alpha_{TR} lnTR_{t-1} + \sum_{i=1}^{p} \vartheta_i \Delta lnFD_{t-1} + \sum_{j=0}^{q} \vartheta_j \Delta lnC_{t-1} + \sum_{k=0}^{r} \vartheta_k \Delta lnEC_{t-1} + \sum_{l=0}^{s} \vartheta_l \Delta lnG_{t-1} + \sum_{m=0}^{t} \vartheta_m \Delta lnTR_{t-1} + \mu_t \ldots\ldots\ldots (9)$$

$$\Delta lnTR_t = \alpha_1 + \alpha_{DUM}DUM + \alpha_C lnC_{t-1} + \alpha_{EC} lnEC_{t-1} + \alpha_G lnG_{t-1} + \alpha_{FD} lnFD_{t-1} + \alpha_{TR} lnTR_{t-1} + \sum_{i=1}^{p} \emptyset_i \Delta lnTR_{t-1} + \sum_{j=0}^{q} \emptyset_j \Delta lnC_{t-1} + \sum_{k=0}^{r} \emptyset_k \Delta lnEC_{t-1} + \sum_{l=0}^{s} \emptyset_l \Delta lnFD_{t-1} + \sum_{m=0}^{t} \emptyset_m \Delta lnG_{t-1} + \mu_t \ldots\ldots\ldots (10)$$

The first difference operator is represented by Δ while π_t denotes residual terms. The optimal lag length for the first-difference regression was determined by the lowest Akaike Information Criterion (AIC) value. The F-statistic is considerably more responsive to lag order selection, and an incorrect lag length choice may yield misleading outcomes. (75) devised an F-test to assess the combined significance of the lagged level variables' coefficients. For instance, in equation (3), the null hypothesis of no cointegration among variables is $H_0: \alpha_c = \alpha_{EC} = \alpha_G = \alpha_{FD} = \alpha_{TR} = 0$, whereas the alternative hypothesis of cointegration is $H_A: \alpha_c \neq \alpha_{EC} \neq \alpha_G \neq \alpha_{FD} \neq \alpha_{TR} \neq 0$. (75) established two asymptotic critical values: the upper critical bound (UCB) and lower critical bound (LCB), which are utilized to determine the presence of cointegration between series. The LCB is employed to test cointegration if all the series are integrated at I(0); otherwise, the UCB is used. The calculated F-statistics for equations (6) to (10) are F_c (C / EC, G , FD , TR) , F_E (EC / C , G , FD , TR) , F_G (G / C , EC, FD ,TR) , F_{FD} (FD / C, E,Y ,TR) and F_{TR} (TR / C, E,Y , F), respectively. A long-term relationship between variables is established when the calculated F-statistic surpasses the upper critical bound (UCB). Cointegration is absent if the F-statistic is below the lower critical bound (LCB). The cointegration status remains inconclusive when the F-statistic lies between the LCB and UCB. In such cases, an error correction method serves as a convenient and appropriate approach for examining the cointegration among variables. We opted to use the critical bounds generated by (78) for cointegration testing rather than this from (79). After confirming the cointegration among the variables, we employed the VECM Granger causality approach to investigate the causal relationships between economic growth, energy consumption, financial development, and CO2 emissions. (80) suggested that the vector error correction method (VECM) is more suitable for analyzing causality between series when variables are integrated into me (1). The VECM is a constrained version of the unrestricted VAR (vector autoregressive) model, with the constraint imposed by the existence of a long-term relationship between the series. The error correction model (ECM) system treats all series as endogenous. This framework allows the predicted variable to be explained by its own lags, lags of forcing variables, error correction terms, and residual terms. The VECM equations were formulated as follows:

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$$(1-L)\begin{bmatrix} C_t \\ G_t \\ EC_t \\ FD_t \\ TR_t \end{bmatrix} = \begin{bmatrix} \emptyset_1 \\ \emptyset_2 \\ \emptyset_3 \\ \emptyset_4 \\ \emptyset_5 \end{bmatrix} + \sum_{i=1}^{y}(1-L)\begin{bmatrix} a_{11i}a_{12i}a_{13i}a_{14i}a_{15i} \\ b_{11i}b_{12i}b_{13i}b_{14i}b_{15i} \\ \emptyset_{11i}\emptyset_{12i}\emptyset_{13i}\emptyset_{14i}\emptyset_{15i} \\ \delta_{11i}\delta_{12i}\delta_{13i}\delta_{14i}\delta_{15i} \\ \gamma_{11i}\gamma_{12i}\gamma_{13i}\gamma_{14i}\gamma_{15i} \end{bmatrix} X \begin{bmatrix} C_{t-i} \\ G_{t-j} \\ EC_{t-k} \\ FD_{t-l} \\ TR_{t-m} \end{bmatrix} + \begin{bmatrix} \alpha \\ \beta \\ \gamma \\ \delta \\ \rho \end{bmatrix} ECM_{t-1} + \begin{bmatrix} \vartheta_{1t} \\ \vartheta_{2t} \\ \vartheta_{3t} \\ \vartheta_{4t} \\ \vartheta_{5t} \end{bmatrix}$$

In this context, μ_{it} represents random variables that are assumed to have normal distributions with zero means and constant variances. The established long-term relationship between the series is further validated by the statistical significance of the lagged error term, ECT_{t-1}. The estimates of ECT_{t-1} also indicate the rate at which short-term deviations converge towards the long-term equilibrium path. When a series is found to be cointegrated, the vector error correction method (VECM) is suitable for examining causality between variables, with causality expected in at least one direction. The VECM differentiates between short- and long-term causal relationships and is employed to detect causality in the long run, short run, and jointly. The t-statistic of the lagged error term estimate $ECT_{t-1}$with a negative sign is used to test long-run causal relationships, while the joint X^2 statistical significance of the first-difference-lagged independent variable estimates is used to investigate short-run causality. Economic growth is said to Granger cause carbon emissions if $\alpha_{22,i} \neq 0\forall_i$ is found to be statistically significant. Conversely, if $\beta_{22,i} \neq 0\forall_i$ is statistically significant, causality flows from CO2 emissions to economic growth. Similar inferences can be made for the other causal hypotheses. Joint causality (long and short runs) is examined using the Wald or F-test for the joint significance of the lagged term estimates of the independent variables and the error correction term. The presence of both short- and long-term causal relationships between variables is referred to as a strong Granger causality (3).

Results and their Discussion

To explores the long-term relationship between economic growth, energy consumption, financial development, trade openness, and CO2 emissions in Bangladesh, we utilized the ARDL bound testing approach. This method provides flexibility in terms of the integration order of the series, allowing variables to be integrated at I(0), I(1), or a mix of both. However, the ARDL F-statistic loses its validity if any variable is stationary at I(2) or higher. To confirm that all variables were integrated at I(0) or I(1), we applied the Zivot-Andrews structural break trended unit root test. The outcomes of this test are detailed in Table 1(74). The findings indicate that all series exhibit unit root problems at their level but achieve integration at I(1), demonstrating stationarity in their first differenced form. Given this consistent integration level across variables, we proceeded to assess the presence of a long-term relationship among the aforementioned factors using the ARDL bounds testing approach to cointegration. This analysis incorporated structural breaks in the series covering the period from 1980Q1 to 2020Q4.

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Table-1: Zivot-Andrews Structural Break Trended Unit Root Test

Variable	Level		First difference	
	T-Test	**Time Break**	**T-Test**	**Time Break**
LnC_t	-4.716 (1)	$1993Q_1$	-8.555 (3)*	$1982Q_4$
LnG_t	-3.457 (1)	$1997Q_4$	-9.038 (3)*	$1997Q_3$
$LnEC_t$	-3.486 (2)	$1989Q_3$	-8.948 (2)*	$1985Q_3$
$LnTR_t$	-4.797 (2)	$1987Q_3$	-11.625 (3)*	$1988Q_4$
$LnFD_t$	4.932 (1)	$1988Q_3$	6.369 (3)	$1997Q_3$

Note: * denotes significance at the 1% level. The lag order is indicated in parentheses.

Prior to conducting the ARDL bounds testing, it is crucial to determine the optimal lag order for the variables to compute the appropriate ARDL F-statistic and assess the presence of cointegration among the variables. The F-test calculation is highly dependent on the choice of lag length (81). A lag length of 6 was selected based on the minimum Akaike Information Criterion (AIC) value. The AIC criterion exhibits stronger power properties compared to the SBC and provides efficient and dependable results, effectively capturing the dynamic relationships within the series (82). The next step involves employing the F-test to examine long-run cointegration among the variables. Table 2 displays the outcomes of the ARDL bounds testing approach to cointegration, accounting for structural breaks in the series. The findings reveal that the computed F-statistics surpass the upper critical bound at both the 5 percent and 1 percent significance levels when CO2 emissions, energy consumption, economic growth, and trade openness are considered as predicted variables.

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BOUNDS TESTING ANALYSIS				**DIAGNOSTIC TESTS**			
ESTIMATED MODELS	Optimal lag length	Structural Break	F-statistics	X^2_{Normal}	X^2_{ARCH}	X^2_{RESET}	X^2_{SERIAL}
F_C (C / EC, FD, G, TR)	6, 6, 6, 6, 5	1994Q1	3.738**	0.7966	[1]: 0.2803	[1]: 2.5183	[1]: 0.0102; [2]: 0.181
F_G (Y / C, EC, FD, TR)	6, 6, 6, 6, 6	1998Q4	3.640**	2.8025	[1]: 1.2024	[1]: 0.5163	[1]: 2.0238; [2]: 1.2908
F_{EC} (EC / C, G, FD, TR)	6, 6, 6, 6, 5	1989Q3	4.894*	2.2403	[1]: 0.2039	[1]: 2.55459	[1]: 0.6996; [2]: 1.1053
F_{TR} (TR / C, EC, G, FD)	6, 6, 5, 5, 6	1988Q3	4.157*	0.5441	[1]: 1.1454	[1]: 0.2764	[1]: 3.1246; [2]: 1.5479
F_{FD} (FD / C, EC, G, TR)	6, 6, 6, 6, 6	1989Q3	1.644	2.1623	[1]: 3.1388	[2]: 0.0751	[1]: 8.5418; [3]: 1.5835
SIGNIFICANCE LEVEL	Critical values (T= 148)						
	Lower bounds *I*(0)	Upper Bound I(1)					
1 PERCENT LEVEL	2.89	3.98					
5 PERCENT LEVEL	2.28	3.29					
10 PERCENT LEVEL	1.98	2.95					

Table 2: The Results of the ARDL Cointegration Test
Note: * and ** denotes significance at 1% and 5 % at levels respectively

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The results require the rejection of the null hypothesis of no cointegration, as the evidence demonstrates the presence of four cointegrating vectors. This finding confirms a stable long-term equilibrium relationship among economic growth, energy consumption, financial development, trade openness, and CO_2 emissions in Bangladesh. Furthermore, the study identifies structural breaks in the analyzed time series: CO_2 emissions in 1994Q1, economic growth in 1998Q4, energy consumption in 1989Q3, and trade openness in 1988Q3.

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Table-3: Long-and-short Runs Analysis
DEPENDENT VARIABLE = LN C_T

LONG RUN ANALYSIS				
VARIABLES	**Coefficient**	**T-Statistic**	**Coefficient**	**T-Statistic**
CONSTANT	-3.1365*	-11.8566	-4.4764*	-16.9072
LN ET	0.6794*	4.4002	0.5722*	4.5435
LN YT	0.7088*	6.2679	0.8861*	9.4193
LN FT	-0.2072*	-2.1148	0.5087*	8.2469
LN F 2	….	….	-0.0858*	-8.6553
LN TRT	-0.1666*	-3.3943	-0.1586*	-3.9781
SHORT RUN ANALYSIS				
VARIABLES	**Coefficient**	**T-Statistic**	**Coefficient**	**T-Statistic**
CONSTANT	-0.0006	-0.9758	-0.00089	-1.5195
LN ET	0.5952*	3.4511	0.6248***	1.8846
LN YT	0.9793*	6.5649	0.9856*	4.5829
LN FT	0.0419***	1.8202	0.0373**	1.9986
LN F 2	….	….	0.4384**	2.0577
LN TRT	-0.2268*	-6.6962	-0.1966*	-4.6753
ECM_{T-1}	-0.0661*	-2.7589	-0.0456***	-1.6651
R2	0.6273		0.6225	
F-STATISTIC	46.4383*		37.6448*	
SHORT-RUN DIAGNOSTIC TESTS				
TEST	**F-statistic**	**Prob. value**	**F-statistic**	**Prob. value**
X^2 ARCH	2.2586	0.1352	1.4935	0.2099
X^2 WHITE	1.3647	0.1317	1.2988	0.1318
X^2 RAMSAY	1.8448	0.1239	1.8958	0.1189

NOTE: * AND ** SHOW SIGNIFICANCE AT 1 AND 5 PER CENT LEVEL OF SIGNIFICANCE RESPECTIVELY.

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After examining the long-term relationship between variables, the next step involves assessing the marginal effects of economic growth, energy consumption, financial development, and trade openness on CO_2 emissions. The results in Table 3 indicate that energy consumption has a positive and statistically significant impact on CO_2 emissions, suggesting that higher energy consumption significantly contributes to energy pollution, second only to economic growth. Specifically, a 1 percent rise in energy consumption corresponds to a 0.6794 percent increase in CO_2 emissions, assuming other factors remain constant. Similarly, economic growth shows a positive and significant relationship with CO_2 emissions at the 1 percent level, with a 1 percent increase in economic growth leading to a 0.7088 percent rise in CO_2 emissions. The analysis confirms that economic growth is a major driver of CO_2 emissions in Bangladesh.

In contrast, financial development has a statistically significant negative effect on CO_2 emissions at the 1 percent level, implying that a 1 percent increase in financial development reduces CO_2 emissions by 0.2072 percent. This finding highlights the role of the financial sector in promoting environmentally friendly investments, thereby reducing emissions. Trade openness also exhibits a negative and statistically significant relationship with CO_2 emissions at the 1 percent level, indicating that increased trade openness enables developing economies to adopt advanced, low-emission technologies. A 1 percent increase in trade openness results in a 0.1666 percent decrease in CO_2 emissions. Furthermore, the analysis reveals an inverted U-shaped relationship between financial development and CO_2 emissions, where the linear term of financial development has a positive impact and the nonlinear term has a negative impact, both significant at the 1 percent level. This suggests that while CO_2 emissions initially rise with financial development, they eventually decline as the financial sector matures. To foster a cleaner environment, the financial sector should support energy-efficient technologies and renewable energy projects through loans or subsidies.

In the short term, both energy consumption and economic growth have a positive and statistically significant impact on carbon emissions at the 1 percent level, affirming that economic growth is a major driver of emissions. Financial sector development exhibits a positive relationship with CO_2 emissions, significant at the 10 percent level, whereas trade openness is negatively associated with emissions. The linear and nonlinear impacts of financial development on CO_2 emissions are both positive and statistically significant at the 5 percent level, with no indication of an inverted-U or U-shaped relationship. The lagged error term ECM_{t-1}, with a statistically significant negative coefficient of -0.0661 (-0.0456) at the 1(10) percent level, confirms the long-term relationship between the variables. This indicates that CO_2 emissions adjust by 6.61 (4.56) percent per quarter, with full convergence expected in three years and three quarters (five years and two quarters). This rapid adjustment reflects Bangladesh's economy's responsiveness to shocks in the carbon emission equation.

Table 3 also presents diagnostic test results for the short-run model, which successfully passes tests for autoregressive conditional heteroskedasticity, white heteroskedasticity, and model specification. These results confirm the absence of

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heteroscedasticity issues, homoscedasticity of variables, and a well-structured functional form, ensuring the consistency and stability of the short-run empirical evidence for policymaking on carbon emissions in Bangladesh.

The existence of cointegration among long-term economic growth, energy consumption, financial development, trade openness, and carbon emissions necessitated the application of the VECM Granger causality method to investigate causal relationships. Understanding these causal directions enables policymakers to formulate integrated strategies for energy, economic, financial, trade, and environmental policies that sustain economic growth while enhancing environmental quality. According to reference (80), when cointegration is present and variables are stationary of the first order, the VECM Granger causality framework is suitable for identifying both long-term and short-term causal links among these variables. Table 4 presents the Granger causality test results, revealing a bidirectional causality between energy consumption and CO_2 emissions in the long term. This finding aligns with prior energy literature, notably references (83) and (58) for Greece, indicating that decoupling carbon emissions remains a challenge for Bangladesh. A comprehensive review of the energy structure is essential to promote energy-efficient technologies through policy reforms. The feedback effect between economic growth and CO_2 emissions highlights the necessity of adopting energy-efficient technologies to boost domestic production while reducing emissions. Furthermore, trade openness and CO_2 emissions show mutual Granger causality.

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Table 4: The VECM Granger Causality Analysis

DEPENDENT DIRECTION OF CAUSALITY

VARIABLE	**Short Run**					**Long Run**	**Joint Long-and-Short-Run Causality**				
	ΔlnC_{t-1}	$\Delta lnEC_{t-1}$	ΔlnG_{t-1}	$\Delta lnFD_{t-1}$	$\Delta lnTR_{t-1}$	ECT_{t-1}	$\Delta lnC_{t-1}, ECT_{t-1}$	$\Delta lnEC_{t-1}, ECT_{t-1}$	$\Delta lnG_{t-1}, ECT_{t-1}$	$\Delta lnFD_{t-1}, ECT_{t-1}$	$\Delta lnTR_{t-1}, ECT_{t-1}$
ΔlnC_t	....	8.6547* [0.0002]	26.2338* [0.0001]	0.1985 [0.8201]	20.7218* [0.0001]	-0.0642* [-3.6242]	....	12.6547* [0.0001]	21.6458* [0.0003]	5.1928* [0.003]	18.9304* [0.0002]
$\Delta lnEC_t$	12.2849* [0.0001]	....	0.5177 [0.5968]	1.2593 [0.3872]	0.5733 [0.5651]	-0.0345*** [-1.8654]	8.5511* [0.0001]	....	2.4969*** [0.0626]	2.9508** [0.0526]	2.0406*** [0.1012]
ΔlnG_t	23.4327* [0.0000]	0.7468 [0.4758]	....	0.6857 [0.5056]	0.3238 [0.7241]	-0.0333** [-2.4719]	18.1811 [0.0000]	2.2995*** [0.0803]	....	2.2018*** [0.0908]	3.4321** [0.0188]
$\Delta lnFD_t$	1.8418 [0.1625]	1.2552 [0.2884]	3.6709** [0.0281]	....	4.2192** [0.0168]	....	....	....	....	....	....
$\Delta lnTR_t$	20.3998* [0.0000]	0.1616 [0.8511]	0.8531 [0.4285]	17.2248* [0.0001]	**....**	-0.1063* [-4.1463]	20.3191* [0.0000]	6.2683* [0.0001]	5.8403* [0.0003]	21.4441* [0.0002]	**....**

Note: *, ** and *** show significance at 1, 5 and 10 per cent levels respectively.

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This study identifies reciprocal causal relationships between economic expansion and energy consumption, trade liberalization and economic growth, as well as trade liberalization and energy use. The development of the financial sector is shown to Granger-cause carbon emissions, energy consumption, economic expansion, and trade openness. A unidirectional causal relationship exists between financial development and CO_2 emissions, supporting the notion that advancements in the financial sector decrease carbon emissions by facilitating the adoption of cleaner, more advanced production technologies. These results align with the existing energy literature, such as the work of (68). The Granger causality from financial development to energy consumption supports the argument, as discussed by (15), that a robust financial sector enables firms to integrate energy-efficient technologies into their production processes. The supply-side hypothesis is validated, as the analysis indicates that economic growth and trade openness Cause financial development. In the short term, a bidirectional causal relationship is observed between energy consumption and CO_2 emissions. Mutual causality is also evident between economic growth and carbon emissions, as well as between CO_2 emissions and trade openness. The feedback hypothesis endorses the link between economic growth and carbon emissions. A unidirectional causal relationship is identified between economic growth and financial development, while financial development Granger causes trade openness. The combined long- and short-term causality analyses reinforce these empirical findings across both time horizons. Economic literature highlights limitations in Granger causality methods, including the VECM Granger causality test, which does not assess the strength of causal relationships beyond the specified timeframe, thereby reducing the reliability of the results. This study employs the Innovative Accounting Approach (IAA) to address this limitation by incorporating variance decomposition and impulse response function techniques. Specifically, we utilize the generalized forecast error variance decomposition method within a vector autoregressive (VAR) framework to assess the strength of causal relationships among economic growth, energy consumption, financial development, trade openness, and CO_2 emissions in Bangladesh. The variance decomposition method quantifies the proportion of forecast error variance in a series attributable to innovations in each independent variable over various time horizons. (75) noted that this method illustrates the proportional impact of shocks in one variable on another. Its key advantage lies in its independence from variable ordering, as the VAR system inherently determines this aspect. Additionally, it evaluates the effects of simultaneous shocks. (76) argued that the variance decomposition approach provides more robust results than traditional methods within the VAR framework. Table 5 presents the variance decomposition results, indicating that 46.14% of CO_2 emissions are due to its own shocks, while a one-standard-deviation shock in energy consumption accounts for 20.24% of energy-related pollutants. Economic growth contributes 19.37% to CO_2 emissions following a standard shock, with this contribution initially increasing, peaking, and then declining, confirming an inverted-U relationship between economic growth and CO_2 emissions in Bangladesh. Financial development and trade openness have minimal impacts on CO_2 emissions, contributing 3.12% and 8.69%, respectively.

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Table-5: Variance Decomposition Approach Variance Decomposition of $\ln C_t$

Period	S.E.	$\ln C_t$	$\ln EC_t$	$\ln G_t$	$\ln FD_t$	$\ln TR_t$
1	0.0048	100.0000	0.0000	0.0000	0.0000	0.0000
2	0.0084	98.4468	0.0069	0.8215	0.2542	0.4707
3	0.0118	95.8617	0.0058	2.5728	0.4254	1.1344
4	0.0151	92.4786	0.0057	5.1278	0.4953	1.8927
5	0.0167	87.7278	0.0626	7.95207	1.3502	2.9074
6	0.0178	82.8781	0.3653	11.0312	2.0656	3.6598
7	0.0187	77.4638	1.1938	14.2045	2.7761	4.3621
8	0.0195	71.7385	2.8087	16.9598	3.4691	5.0238
9	0.0203	66.4172	5.3386	19.0871	3.4831	5.6742
10	0.0212	61.3778	8.4017	20.2445	3.4089	6.5672
11	0.0218	57.0434	11.583	20.5078	3.2717	7.5934
12	0.0227	53.4904	14.5400	20.1672	3.1162	8.6864
13	0.0233	50.5063	16.8910	19.7574	3.0308	9.8147
14	0.0239	48.1258	18.7645	19.3684	2.9628	10.7741
15	0.0244	46.1345	20.2357	19.1182	2.9064	11.6053

Variance Decomposition of $\ln EC_t$

Period	S.E.	$\ln C_t$	$\ln EC_t$	$\ln G_t$	$\ln FD_t$	$\ln TR_t$
1	0.0018	17.4032	82.5968	0.0000	0.0000	0.0000
2	0.0032	14.4026	85.1169	0.2189	0.0145	0.2472
3	0.0047	11.7135	86.8747	0.7851	0.0133	0.6136
4	0.0063	9.3628	87.9545	1.6258	0.0075	1.0496
5	0.0074	6.9612	88.0054	3.4014	0.0155	1.6167
6	0.0083	5.4919	87.2236	5.2246	0.0123	2.0478
7	0.0091	4.7469	85.6814	7.0327	0.0127	2.5265
8	0.0098	4.5355	83.6185	8.7407	0.0175	3.0879

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9	0.0106	4.0188	82.5120	9.6001	0.0746	3.7945
10	0.0113	3.6028	81.3141	10.1828	0.1294	4.7709
11	0.0121	3.2372	80.2796	10.4542	0.1868	5.8421
12	0.0128	2.9078	79.4237	10.4947	0.2478	6.9258
13	0.0135	2.7607	78.2502	10.8087	0.2674	7.9132
14	0.0141	2.6312	77.1846	11.1829	0.2918	8.7096
15	0.0147	2.5178	76.0203	11.7489	0.3159	9.3971

Variance Decomposition of $\ln G_t$

Period	S.E.	$\ln C_t$	$\ln EC_t$	$\ln G_t$	$\ln FD_t$	$\ln TR_t$
1	0.0021	40.6419	2.0541	57.3038	0.0000	0.0000
2	0.0039	36.2333	2.0890	61.4501	6.37E-04	0.2277
3	0.0058	33.0523	2.3100	63.9149	0.0206	0.70234
4	0.0083	30.4171	2.6485	65.4593	0.0707	1.4046
5	0.0099	27.5973	2.8743	66.6822	0.0507	2.7957
6	0.0113	25.0909	3.2657	67.1882	0.0431	4.4122
7	0.012619	22.85859	3.746154	67.0481	0.0511	6.2961
8	0.013807	20.92356	4.284033	66.2997	0.0797	8.4128
9	0.014972	19.27542	5.226381	65.1770	0.0747	10.2466
10	0.016053	17.95612	6.289860	63.5758	0.0694	12.1089
11	0.017059	16.88245	7.482407	61.6820	0.0638	13.8894
12	0.017993	15.99703	8.763326	59.6560	0.0584	15.5253
13	0.018908	15.39428	9.722401	57.6800	0.0542	17.1493
14	0.019798	14.90388	10.51059	55.9342	0.0516	18.5998
15	0.020678	14.55143	11.05967	54.4609	0.0488	19.8791

Variance Decomposition of $\ln FD_t$

Period	S.E.	$\ln C_t$	$\ln EC_t$	$\ln G_t$	$\ln FD_t$	$\ln TR_t$
1	0.0058	1.1566	11.2437	8.4014	79.1981	0.0000
2	0.0106	0.9545	12.0715	10.8951	75.9502	0.1284
3	0.0151	0.8773	13.0946	13.6163	71.7451	0.6668

4	0.0196	0.8228	14.0305	16.2982	67.1848	1.6639
5	0.0262	5.9224	10.1966	28.5081	51.3399	4.0332
6	0.0343	9.7686	6.9243	39.1115	37.5833	6.6124
7	0.0441	11.9678	4.7259	46.5926	27.9647	8.74915
8	0.0548	13.0698	3.3448	51.5877	21.5328	10.4647
9	0.0628	12.1872	2.8673	54.1395	18.2419	12.5643
10	0.0698	11.2076	2.7349	55.4967	16.0828	14.4779
11	0.0757	10.2506	2.8610	55.9801	14.5583	16.3502
12	0.0807	9.3928	3.1932	55.7808	13.4309	18.2025
13	0.0856	8.7378	3.6396	55.2795	12.6389	19.7044
14	0.0898	8.2305	4.1114	54.4528	12.0381	21.1672
15	0.0938	7.8552	4.5531	53.4621	11.5941	22.5357

Variance Decomposition of $\ln TR_t$

Period	S.E.	$\ln C_t$	$\ln EC_t$	$\ln G_t$	$\ln FD_t$	$\ln TR_t$
1	0.0068	23.2646	4.2113	0.0022	1.3487	71.1733
2	0.0132	23.3915	3.9679	0.6291	0.7488	71.2629
3	0.0195	23.4066	4.0717	2.0349	0.6502	69.8367
4	0.0258	23.3724	4.3120	4.1326	0.7082	67.4749
5	0.0284	20.1513	4.9515	4.7048	0.6975	69.4948
6	0.0298	18.3688	5.7157	4.8375	0.8375	70.2407
7	0.0305	17.8344	6.5153	4.7207	1.2938	69.6358
8	0.0308	18.4339	7.2447	4.5836	2.2498	67.4882
9	0.0312	18.1933	8.2638	4.5217	2.3063	66.7148
10	0.0315	17.9356	9.5590	4.4554	2.3418	65.7083
11	0.0318	17.7918	11.275	4.3691	2.2984	64.2652
12	0.0324	17.9239	13.4355	4.2391	2.2343	62.1674
13	0.0328	17.6608	16.2504	4.0878	2.2456	59.7552
14	0.0338	17.3788	19.3690	3.9075	2.251	57.0929
15	0.0346	17.0876	22.4373	3.7352	2.3281	54.4119

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The variance decomposition analysis revealed that trade openness, financial development, economic growth, and CO_2 emissions contributed 2.5178%, 11.7489%, 0.3159%, and 9.3971% respectively to energy consumption fluctuations, with the residual variance explained by energy consumption's own innovative shocks. A one standard deviation shock to economic growth accounted for 54.47% of its own variance. CO_2 emissions and energy consumption explained 14.56% and 11.06% of economic growth variations, respectively. Trade openness contributed 19.88% to economic growth variance through a standard shock. In financial development, 7.86% of its variance stemmed from CO_2 emissions shocks, while energy consumption shocks accounted for 4.56%. Financial development's variance was also influenced by 11.58% of its own innovative shocks, with economic growth and trade openness explaining 53.47% and 22.54% of its fluctuations via standard shocks. For economic growth, 17.09% and 22.44% of its variance were attributed to CO_2 emissions and energy consumption shocks, respectively. Trade openness showed limited sensitivity to economic growth (3.74%) and financial development (2.33%), with 54.42% of its variance explained by its own shocks.

The impulse response function analysis demonstrated in Figure 1 shows the dynamic interrelationships: CO_2 emissions responded positively to energy consumption shocks and exhibited an inverted U-shaped reaction to economic growth, peaking before declining. Financial development and trade openness negatively influenced CO_2 emissions, suggesting environmentally beneficial effects. Energy consumption displayed an initial rise followed by a decline, eventually turning negative in response to CO_2 emissions shocks. Economic growth positively drove energy demand, while financial development initially reduced consumption before a delayed positive response. Trade openness improved environmental quality by lowering CO_2 emissions. Economic growth was positively linked to CO_2 emissions and energy consumption but negatively affected by trade openness, with financial development's role remaining ambiguous. Financial development benefited from energy consumption and economic growth shocks but was hindered by trade openness shocks. Trade openness exhibited oscillatory responses to CO_2 emissions and economic growth shocks, while energy consumption's impact on trade openness strengthened over time.

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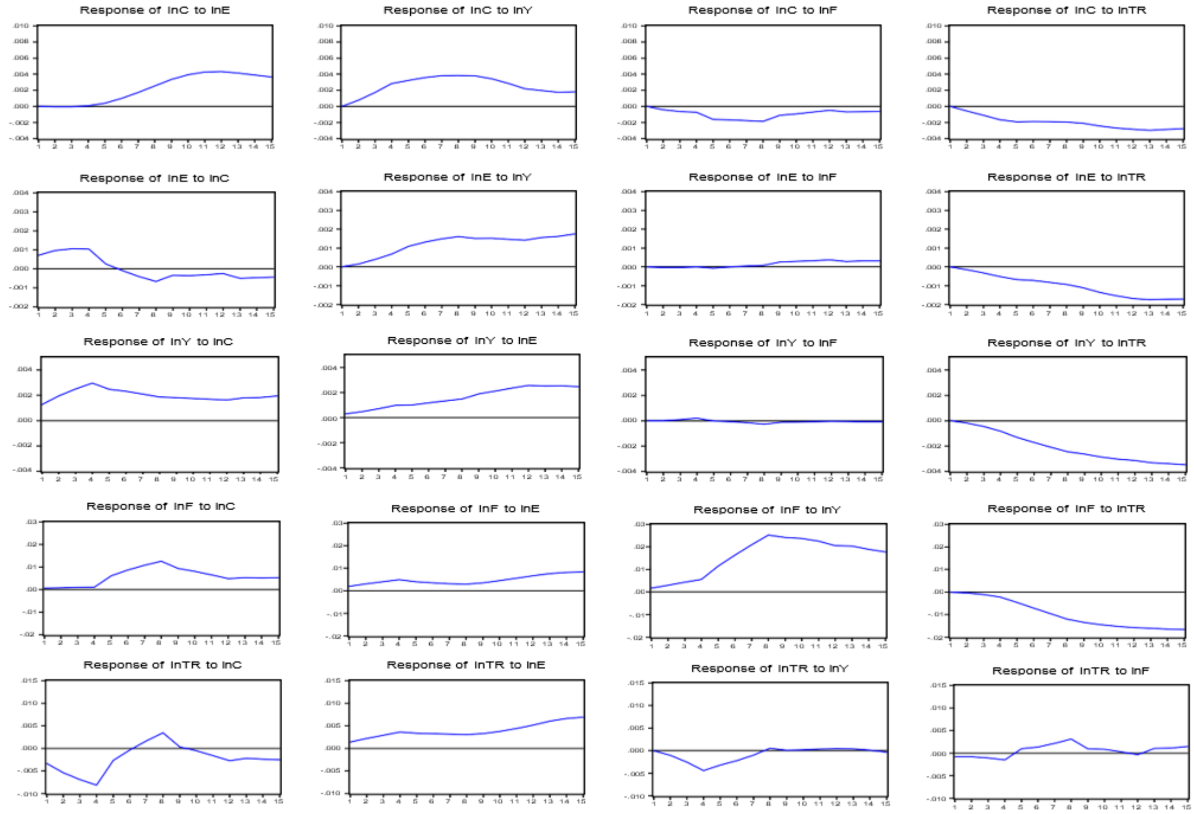
Figure 1: Impulse Response Function



Conclusion and Future Direction

Bangladesh's pursuit of economic growth amid escalating energy demands has created a complex interplay between development and environmental sustainability. This study, spanning four decades of data, reveals a critical finding: economic expansion and energy consumption are significant drivers of CO_2 emissions ((10); (84); however, strategic financial development and trade openness offer potential pathways to mitigate environmental harm ((85); (34)). The bidirectional causality between energy use and emissions underscores an urgent challenge—decoupling growth from carbon-intensive practices is not merely ideal but imperative (86). Concurrently, the financial sector emerges as a crucial factor, its maturation enabling cleaner technologies and fostering an inverted U-shaped relationship with emissions (i.e., the Environmental Kuznets Curve), wherein initial industrial growth transitions to more environmentally favorable outcomes (87). Trade openness further amplifies this trend, functioning as a conduit for advanced, low-emission technologies (60).

The feedback loops between economic growth, energy use, and emissions necessitate a paradigm shift. Policymakers must recognize that traditional growth models are environmentally unsustainable (88). Instead, Bangladesh's strategy should integrate energy efficiency, sustainable finance, and trade policies that prioritize green innovation. For instance, incentivizing renewable energy investments through targeted financial instruments—such as green bonds and low-interest loans for environmentally beneficial projects—could align economic and environmental objectives (89). Similarly, leveraging trade partnerships to import cutting-edge clean technologies can accelerate decarbonization without impeding development (90).

Future Research and Policy Agendas

The findings from this study provide a foundation for transformative research and policy agendas:

1. **Renewable Energy Transition**: Investigate how transitioning from fossil fuels to renewable sources (solar, wind) could disrupt the energy-emission nexus, utilizing frameworks that account for Bangladesh's geographic and economic contexts (91).
2. **Urbanization and Smart Cities**: Rapid urbanization intensifies energy demands. Future research should explore smart city models that integrate energy-efficient infrastructure, public transportation, and waste management systems (92).
3. **Global Climate Synergy**: Align national policies with international climate commitments (e.g., Paris Agreement). Research could evaluate how carbon pricing, cross-border green financing, and climate adaptation funds might enhance Bangladesh's resilience (93).
4. **Industrial Innovation**: Examine the potential role of Industry 4.0 technologies—AI, IoT—in optimizing energy use across manufacturing sectors, a critical driver of GDP and emissions (94).
5. **Social Equity in Green Policies**: Ensure decarbonization strategies do not marginalize vulnerable populations. Studies on equitable access to clean energy and employment generation in green sectors are essential (95).

Bangladesh is at a critical juncture. The imperative is clear: adopt a growth model where economic progress and environmental stewardship are mutually reinforcing. By leveraging financial innovation, global trade networks, and policy adaptability, the nation can establish a trajectory toward sustainable prosperity—a paradigm not only for survival but for leadership in the global green economy (96). The period for incremental change has concluded; the era of bold, integrated action commences now.

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