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Energy Transition, Financial Development, and Load Capacity Factor in Bangladesh: Asymmetric Effects and Rapid Renewable Growth

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Abstract

Can renewable energy alone restore ecological balance in Bangladesh? We investigate the asymmetric and distributional effects of energy transition and financial development on the Load Capacity Factor (LCF) from 1976 to 2024. Using NARDL, quantile ARDL, Fourier breaks, and scenario forecasting, we find that fossil fuels undermine ecological sustainability in the long run, while renewable energy does not exhibit a statistically significant long-run effect due to the limited share of renewables in the energy mix rather than an absence of environmental benefits. The analysis also finds no robust evidence of credit asymmetry, and the short-run impact of renewable energy remains broadly similar across different levels of ecological deficit. Looking ahead, scenario forecasts indicate that only a swift transition to renewable energy or a Net Zero pathway can elevate the LCF above the sustainability threshold by the late 2030s. The findings highlight the importance of speeding up renewable energy deployment and directing finance towards sustainable investments.

JEL Classification: Q53, Q56, Q42, Q43, C22, G21, O16, O13

1. Introduction

The global ecological crisis presents a major challenge to environmental sustainability, especially in regions where ecological demands exceed natural capacity. Evidence shows that ecological footprints often exceed biocapacity, leading to environmental degradation and increasing climate-related risks (Shi & Smith, 2025; Rasheed et al., 2023). A more comprehensive indicator is the Load Capacity Factor (LCF), defined as the ratio of biocapacity to ecological footprint. In many developing economies, economic growth intensifies environmental stress unless it is encouraged by cleaner energy sources and technological advancements to mitigate environmental issues (Nguyen et al., 2024; Riaz et al., 2024). The Environmental Kuznets Curve indicates that environmental damage generally rises during early development phases but can decline with better technology and stronger governance (Shi & Smith, 2025; Riaz et al., 2024). This highlights the importance of policy decisions, especially in vulnerable regions like South Asia, where environmental pressures are already significant (Rasheed et al., 2023; Nguyen et al., 2024).

Among South Asian countries, Bangladesh is one of the countries that faces serious environmental challenges. This country's rapid economic growth, industrialisation and urban expansion have increased energy demand; however, much of this demand is still met by fossil fuels. This dependence has increased the ecological footprint and amplified environmental risks, particularly in coastal regions (Qamruzzaman, 2024; Mallik et al., 2025). Although the country's financial development and increased trade openness have supported economic activity, they have also intensified environmental pressure (Qamruzzaman, 2023; Ulfat et al., 2025). Policy makers, the ministry and the Bangladesh Bank aim to boost renewable energy and promote green finance (Qamruzzaman, 2024; Mallik et al., 2025; Kibria et al., 2021; Nam et al., 2024); however, the share of renewable energy is still significantly limited, and the load capacity factor continues to decline. This emphasises the urgent need to manage the transition to a more sustainable energy system that encourages growth without increasing ecological strain (Qamruzzaman, 2023a; Ulfat et al., 2025). However, most current studies assume linear relationships, which may conceal significant nuances.

Most of the literature assumes linear and symmetric impacts of energy use and financial development. This overlooks the complexity of ecological sustainability in Bangladesh. For example, increases in fossil fuel consumption often cause greater environmental harm; however, their reductions do not always result in similar improvements. Financial development also has uneven effects, where credit expansion may stimulate growth but can increase environmental stress depending on investment allocation (Omoke et al., 2020). Moreover, most studies concentrate on average effects, disregarding differences across levels of ecological stress (Kibria et al., 2021; Nasrullah et al., 2021). Structural changes, such as recent policy shifts and economic reforms, are also rarely recognised (Boufateh, 2021; Nasrullah et al., 2021). No previous study has simultaneously examined asymmetric credit effects, quantile heterogeneity, and structural breaks in the LCF for Bangladesh.To address this research gap, the present study explores three main research questions to find the answers. First, whether renewable energy, fossil fuels, and domestic credit have asymmetrical long-term effects on the load capacity factor. Second, whether these effects differ across various levels of ecological stress and structural shifts. Third, how the load capacity factor might develop under different renewable energy scenarios. To address the research question, this study develops three hypotheses concerning asymmetry, heterogeneity, and future sustainability outcomes. First, fossil fuel and credit shocks affect the LCF asymmetrically, while renewable energy shocks are symmetrical. Second, Fossil fuel and credit have stronger negative LCF effects at lower quantiles; the Fourier term and the 2016 break are significant. And Third, Bangladesh can achieve a sustainable LCF by the late 2030s, but only if it commits to a swift renewable energy transition.

This study advances the existing literature in several ways. Firstly, it employs a nonlinear ARDL framework to identify asymmetric relationships between energy consumption, financial development, and ecological sustainability (Qamruzzaman, 2023, 2024). Secondly, it integrates quantile regression with structural break analysis to examine how these relationships vary across levels of ecological stress (Zheng et al., 2022; Özkan et al., 2025). Thirdly, the research provides scenario-based forecasts of the load capacity factor under various renewable energy scenarios. This approach, rarely applied to Bangladesh, offers policy-relevant insights (Qamruzzaman, 2024; Integrating Green Finance, 2025). Given the limited sample size (49 years), the quantile and forecasting results should be interpreted as exploratory. Overall, these contributions provide a more comprehensive and policy-relevant perspective on the relationship among energy, finance, and the environment.

The rest of the paper is organised as follows. Section 2 reviews the literature and develops the hypotheses. Section 3 describes the data, variable construction, and methodology, including ARDL, NARDL, quantile-ARDL, Fourier structural break analysis, and scenario forecasting, using annual data from 1976 to 2024. Section 4 presents the empirical results. Section 5 discusses the findings. Section 6 concludes with a discussion of policy implications and limitations.

2. Literature Review and Hypotheses Development

2.1 Theoretical Framework and Contribution

This study primarily investigates the Environmental Kuznets Curve (EKC) hypothesis, which suggests that environmental pressures tend to increase during the early phases of economic development. However, these pressures may decrease after reaching a certain income threshold due to structural changes, technological advancement, and stricter environmental regulations (Stern, 2023; Usenata, 2018). Moreover, economic activity influences ecological sustainability through scale, composition, and technique effects. As income increases, production and resource consumption expand, yet economies may slowly shift towards cleaner sectors and employ more efficient technologies. Nevertheless, empirical evidence supporting the EKC is inconsistent. Some environmental indicators show that they continue to worsen at higher income levels, particularly in developed countries (Stern, 2017; Genstwa, 2020). In emerging economies such as Bangladesh, the applicability of the EKC is not certain when sustainability is assessed using the Load Capacity Factor rather than conventional emission metrics (Usenata, 2018).

This understanding is supported by complementary theoretical perspectives, which emphasise that environmental outcomes are influenced by complex interactions among demographic, economic, technological, and financial factors. The STIRPAT framework shows that environmental impact is related to population, affluence, and technology, often interacting in nonlinear and asymmetric ways. Additionally, financial development and energy transition theory indicate that economic structures respond differently across contexts. For example, financial innovation and green finance can lower emissions through supporting renewable energy, whereas rapid growth and natural resource extraction tend to increase environmental pressure (Shu et al., 2024; Al-mulali et al., 2024). Other evidence also indicates that the influence of financial development on renewable energy is conditional; it is positive only after certain levels of urbanisation and technological capacity are reached (Wang & Dong, 2021). Together, these perspectives indicate that the links between growth, energy consumption, finance, and ecological capacity are highly context-dependent.

Despite a growing body of literature on environmental sustainability and economic development, several important gaps are still unresolved. Many studies analyse the determinants of environmental sustainability in isolation, paying limited attention to interaction effects and asymmetry. Most focus on carbon emissions rather than broader indicators such as the Load Capacity Factor (LCF), which combines ecological footprint and biocapacity (Kibria, 2021; Sun et al., 2024). Additionally, empirical findings are often inconsistent due to differences in models, data periods, and regional focus. The limited use of quantile-based analysis and advanced techniques, such as Fourier structural break models, further impedes a deeper understanding of dynamic environmental processes (Ali et al., 2025; Integrating Green Finance, 2025). In the case of Bangladesh, the behaviour of the LCF has not been fully explored. To address these research gaps, this study proposes an integrated framework that jointly considers economic growth, energy structure, financial development, and trade openness. Additionally, compared to previous work, it combines nonlinear relationships, asymmetry, structural changes, and distributional differences, thereby providing a more comprehensive and policy-relevant view of ecological sustainability in Bangladesh.

Now we present Fig. 1, which displays the EKC-STIRPAT integrated framework guiding our empirical analysis. The figure organises the theoretical foundations (EKC and STIRPAT) and maps them onto the observed determinants of the Load Capacity Factor. It also highlights where asymmetry, quantile heterogeneity, and structural breaks are incorporated into the model.

2.2 Hypotheses Development

2.2.1 Asymmetric effects of renewable energy, fossil fuel, and financial development

Among energy sources, renewable energy is widely expected to improve environmental quality by reducing emissions and ecological pressure (Reddy et al., 2025; R & R, 2024); however, its actual impact varies based on resource availability, geography, and technology (Kaur & Sharma, 2025). Although some studies indicate that increasing renewable energy use can reduce environmental damage, the reductions do not always fully offset earlier harms (Majeed et al., 2021; Çamkaya et al., 2025). In contrast, fossil fuel consumption consistently causes negative effects. Increases in fossil fuel use tend to cause significant environmental damage, whereas its decrease brings smaller improvements to the ecology, suggesting an asymmetric relationship (Umair et al., 2024; Gandomi et al., 2024). On the other hand, financial development also carries out uneven outcomes. Credit expansion in the country is often linked to higher emissions, whereas contractions do not provide equivalent environmental benefits (Das et al., 2023). In other contexts, financial progress may lessen harm by directing funds into cleaner investments (Afzal et al., 2022). These patterns suggest that assuming symmetry in energy and financial variables can lead to incomplete conclusions. Therefore, it is important to recognise directional asymmetry.

H_1: Fossil fuel and credit shocks affect the LCF asymmetrically, while renewable energy shocks are symmetrical.

2.2.2 Quantile heterogeneity and structural breaks

Previous studies clearly show that environmental relationships may vary across different ecological conditions. Therefore, it is evident that economic and financial variables impact the distribution in different ways. Lower quantiles, which reflect greater ecological stress, generally show very severe negative effects from financial development and energy consumption. In contrast, higher quantiles are associated with better environmental outcomes, aligning with later stages of the EKC (Usman & Jahanger, 2021; Ihezukwu et al., 2025). In developing economies, renewable energy appears more effective at easing pressure at lower quantiles, whereas financial development can sometimes heighten stress (Mehmood & Kaewsaeng-On, 2024). Climate finance generally yields greater benefits in higher-income or more stable contexts (Miao et al., 2024). These findings indicate that policy responses should account for variations across ecological states rather than rely on average effects (Borozan, 2021). On the other hand, structural changes also play a crucial role. Research using Fourier-based techniques demonstrates that gradual shifts in economic and policy conditions are crucial for understanding long-term energy-environment links (Zheng et al., 2022; Yilanci, 2019; Güriş & Sedefoğlu, 2022). In Bangladesh, policy reforms and energy transitions may have altered these relationships since 2016 (Murshed et al., 2021). However, no study has yet investigated both quantile heterogeneity and structural breaks together using the LCF. This restricts our understanding of how environmental responses develop over time and under varying conditions.

H_2: Fossil fuel and credit have stronger negative LCF effects at lower quantiles; the Fourier term and the 2016 break are significant.

2.2.3 Renewable transition scenarios and forecasting

The shift towards renewable energy represents a walk toward environmental sustainability, yet its success depends on technological readiness, policy support, and investment capacity (Reddy et al., 2025; Kaur & Sharma, 2025). In Bangladesh, renewable systems face challenges, such as intermittency and infrastructure constraints, which require coordinated policies and innovation (Sharma, 2024). As a result, recent national initiatives aim is to expand renewable energy and promote green financing (Qamruzzaman, 2024; Mallik et al., 2025). Despite these efforts, the share of renewables remains low, and ecological indicators still show signs of stress (Qamruzzaman, 2023a; Ulfat et al., 2025). Recent studies have not examined scenario-based forecasts of the Load Capacity Factor across various renewable transition pathways in Bangladesh. This gap limits policymakers' ability to set clear targets and assess future outcomes. A faster transition is likely to lead to greater improvements in ecological sustainability than a slower one.

H_3: Bangladesh can achieve a sustainable LCF by the late 2030s, but only if it commits to a swift renewable energy transition.

3. Methodology

3.1 Conceptual foundation and empirical framework

This study builds on the Environmental Kuznets Curve (EKC) hypothesis and the STIRPAT framework. The EKC proposes that environmental pressure increases during early development but may decrease once a certain income level is reached, whereas STIRPAT connects environmental impact to population, affluence, and technology. We expand these frameworks by allowing asymmetric responses to positive and negative shocks and quantile-dependent effects across different levels of ecological stress. The general functional relationship is specified as:

$$\mathrm{LCF}_t = f(\ln\mathrm{GDPPC}_t, \ln\mathrm{GDPPC}_t^2, \mathrm{RENEW}_t, \mathrm{FOSSIL}_t, \mathrm{CREDIT}_t, \mathrm{TRADE}_t)$$

The baseline model is estimated in an error-correction framework, with extensions including nonlinear ARDL for asymmetry, quantile ARDL for distributional effects, and Fourier terms for gradual structural changes. This integrated approach captures both long-term equilibrium relationships and short-term dynamics.

3.2 Data and variable construction

We use annual time-series data for Bangladesh covering 1976 to 2024, giving 49 observations. The dependent variable is the Load Capacity Factor (LCF), defined as the ratio of biocapacity to ecological footprint:

$$\mathrm{LCF_t} = \frac{\mathrm{BIO_t}}{\mathrm{EF_t}}$$

A value greater than one signifies an ecological surplus; below one indicates a deficit. LCF data are sourced from the Global Footprint Network, whereas macroeconomic variables are obtained from the World Bank's World Development Indicators (WDI). The sample period depends on data availability. A structural break dummy, $\mathrm{D2016}$, equals 1 from 2016 onward to account for significant policy shifts, including Bangladesh Bank's sustainable finance guidelines.

We take GDP per capita in natural logarithms to stabilise variance and interpret coefficients as elasticities. All other variables (RENEW, FOSSIL, CREDIT, TRADE) are used in levels (percentages or ratios). Moreover, a squared term, $(\ln\mathrm{GDPPC})^2$, is included to test for an Environmental Kuznets Curve pattern. Renewable and fossil energy shares are perfectly negatively correlated, so they are not included together in the same regression. Zero or negative values are considered missing and missing observations, mainly in early years, are handled through listwise deletion rather than interpolation. Table 1 defines each variable, its measurement, and source.

Table 1
Variable definitions, measurement, and sources

Symbol	Variable	Measurement	Source
LCF	Load Capacity Factor	Ratio of biocapacity to ecological footprint	Global Footprint Network
lnGDPPC	GDP per capita (log)	Constant 2015 US dollars	World Bank WDI
lnGDPPC²	GDP per capita squared	Square of lnGDPPC	Author's calculation
RENEW	Renewable energy consumption	Percentage of total energy consumption	World Bank WDI
FOSSIL	Fossil fuel energy consumption	Percentage of total energy consumption	World Bank WDI
CREDIT	Domestic credit to private sector	Percentage of GDP	World Bank WDI
TRADE	Trade openness	Percentage of GDP	World Bank WDI

3.3 Econometric approach

3.3.1 Unit root and structural break tests

We evaluate stationarity using three complementary tests: the augmented Dickey-Fuller (ADF), the Phillips-Perron (PP), and the Dickey-Fuller GLS (DF-GLS). The DF-GLS test has greater power in small samples. To account for structural breaks, we also utilise the Zivot-Andrews (ZA) test, which allows for one unknown break in the intercept and trend. The ZA test identifies potential break years, guiding the selection of the sharp dummy and Fourier terms. All tests are conducted on the variables in levels and first differences.

3.3.2 Cointegration analysis

We confirm the existence of a long-run equilibrium using three complementary tests. The primary test is the ARDL bounds test (Pesaran, Shin, and Smith, 2001), which is suitable for small samples and mixed integration orders. The unrestricted error correction model is:

$$\Delta \ln LCF_t = \alpha_0 + \sum_{i=1}^{p} \beta_i \Delta \ln LCF_{t-i} + \sum_{j=0}^{q} \gamma_j \Delta X_{t-j} + \delta_1 \ln LCF_{t-1} + \delta_2 X_{t-1} + \psi D2016 + \epsilon_t$$

The null hypothesis of no cointegration is $H_0 : \delta_1 = \delta_2 = 0$, tested using an F-statistic. We also report the Johansen trace test and the Engle-Granger test for robustness. Because the bounds test may be inconclusive for the renewable model, we rely on the significance of the error correction term.

3.3.3 Baseline ARDL model

We estimate the ARDL model in error-correction form. Lag lengths are chosen based on the Akaike information criterion (AIC), with a maximum of three lags, suitable for annual data. The long-run coefficients are derived from the estimated ECM. The error correction term (ECT) must be negative and statistically significant to confirm convergence. We estimate separate models for renewable energy (RENEW) and fossil fuels (FOSSIL) due to their strong negative correlation. Diagnostics include tests for serial correlation (Breusch-Godfrey), heteroskedasticity (Breusch-Pagan), normality (skewness-kurtosis test), and functional form (Ramsey RESET). Parameter stability is evaluated using CUSUM tests.

3.3.4 Nonlinear ARDL (NARDL) for asymmetry

To test asymmetry (H_1), we decompose each variable into positive and negative partial sums following Shin, Yu, and Greenwood-Nimmo (2014). For credit, the decomposition is:

$$CREDIT_t^+ = \sum_{j=1}^{t} \max(\Delta CREDIT_j, 0), CREDIT_t^- = \sum_{j=1}^{t} \min(\Delta CREDIT_j, 0)$$

We then estimate an ARDL model that includes both partial sums. A Wald test examines the null hypothesis of long-run symmetry ($\theta^+ = \theta^-$). We apply this decomposition to RENEW, FOSSIL, and CREDIT separately. Given the small sample size (49 observations), the NARDL results should be interpreted as indicative rather than definitive.

3.3.5 Quantile ARDL (QARDL) for distributional effects

To test whether the marginal effects vary across levels of ecological stress (H_2), we employ the quantile ARDL model of Cho, Kim, and Shin (2015). The quantile error correction representation is:

$$Q_{\Delta \ln LCF_t}(\tau \mid F_{t-1}) = \alpha(\tau) + \sum_{i=1}^{p} \phi_i(\tau) \Delta \ln LCF_{t-i} + \sum_{j=0}^{q} \beta_j(\tau) \Delta Z_{t-j} + \lambda(\tau) ECT_{t-1} + \epsilon_t(\tau)$$

where $\tau \in (0,1)$ indicates the quantile. We estimate three quantiles: $\tau = 0.25$ (high ecological deficit), $\tau = 0.50$ (median), and $\tau = 0.75$ (low ecological deficit). Confidence intervals are obtained by bootstrapping with 1000 replications. Because the sample is small, the QARDL estimates are exploratory.

3.3.6 Fourier ARDL for smooth structural breaks

To capture gradual structural changes that a single dummy cannot fully represent, we augment the ARDL model with Fourier terms at frequency $k = 1$ (Becker, Enders, and Lee, 2006). The Fourier-augmented model is:

$$\Delta \ln LCF_t = \alpha_0 + \rho \ln LCF_{t-1} + \theta X_{t-1} + \sum \gamma_i \Delta \ln LCF_{t-i} + \sum \delta_j \Delta X_{t-j} + \mu_1 \sin 1_t + \mu_2 \cos 1_t + \psi D2016 + \epsilon_t$$

where $\sin 1_t = \sin(2\pi t/T)$ and $\cos 1_t = \cos(2\pi t/T)$. A joint F-test on $\mu_1 = \mu_2 = 0$ tests for the presence of smooth breaks. This approach avoids the loss of degrees of freedom that would come from many discrete dummies.

3.4 Estimation approach and robustness checks

We design our robustness checks in a hierarchical sequence. First, we replace the dependent variable with the ecological footprint (EF) alone. Second, we change the lag selection to the Bayesian information criterion (BIC), allowing up to 2 lags. Third, we add two structural controls: urban population share and agriculture value added. Fourth, we estimate the long-run coefficients using dynamic

ordinary least squares (DOLS) with one lead and one lag. Fifth, we exclude the post-2016 period to test sensitivity to the sharp break. Sixth, we incorporate the Fourier terms as described in Section 3.3.6. All results are compared with the baseline ARDL model.

3.5 Endogeneity and interpretation

Reverse causality cannot be entirely dismissed; for example, low LCF could stimulate investment in renewable energy. The ARDL framework includes lagged dependent variables, which partly address omitted dynamics. DOLS provides an additional correction by including the leads and lags of the differenced regressors. Nonetheless, we interpret our results as long-run conditional associations rather than structural causal estimates. Given the modest sample size (N = 49), we limit the number of lags in all models to a maximum of three, and we treat the NARDL and QARDL results as exploratory. Missing data are handled through listwise deletion, and we report the effective sample size for each model. We revisit these limitations in the discussion section.

3.6 Scenario forecasting

To evaluate H_3, we project the LCF for 2050 under three renewable energy routes. The slow, medium, and fast pathways increase the renewable share by 0.5, 1.0, and 2.0 percentage points per year, respectively. We also simulate a Net Zero pathway following an S-curve. These projections use the long-run elasticity estimated from our ARDL model. All other variables stay at their 2024 values because the historical effect of renewable energy is not statistically significant; these forecasts are only illustrative. They show what could happen if the share of renewables grew much faster than in the past. The analytical workflow is summarised in Fig. 2.

4. Results

We begin with Table 2, which clearly shows that the Load Capacity Factor in Bangladesh is below one throughout the entire sample period, reflecting a consistent ecological deficit, with no signs of a surplus. On the other hand, renewable energy accounts for only about 2.5% of the energy mix, whereas fossil fuels dominate, accounting for nearly 98 percent on average. Domestic credit and trade openness fluctuate considerably over time, indicating substantial financial deepening and growing integration with global markets.

Table 2
Descriptive Statistics (1976–2024)

Variable	N	Mean	Std. Dev.	Min	p25	Median	p75	Max
LCF	54	0.530	0.166	0.283	0.351	0.526	0.700	0.786
lnGDPPC	54	6.512	0.510	5.922	6.083	6.355	6.903	7.571
RENEW (%)	53	2.378	1.660	0.513	0.857	1.831	3.583	5.757
FOSSIL (%)	53	97.622	1.660	94.243	96.417	98.169	99.143	99.487
CREDIT (% of GDP)	51	23.640	13.542	1.917	13.040	20.987	37.799	44.407
TRADE (% of GDP)	54	27.238	9.258	10.996	19.407	26.552	32.098	48.111

We then examine the time-series properties, where unit root tests in Appendix Table A3 indicate that LCF, log GDP per capita, credit, and trade are non-stationary in their levels but become stationary after differencing. Conversely, renewable and fossil shares are already stationary; they reject the unit root hypothesis at the 1 per cent level, which is essential for the models we employ. Meanwhile, cointegration is observed for the fossil fuel specification but not for the renewable one. As Appendix Table A2 confirms, the fossil model produces a bounds F-statistic that significantly exceeds the 5 per cent critical value, and its error correction term is negative and highly significant. In contrast, the renewable model shows no such evidence of a stable long-run relationship. The number of observations varies due to missing early data and the use of lagged variables in model estimation. The effective sample for the ARDL models is 49 observations (1976–2024).

Table 3 presents the long-term baseline results. For fossil fuels, the coefficient is negative and statistically significant at the 1 percent level. A 1-percentage-point increase in the fossil fuel share decreases the LCF by approximately 0.055 units. Since the average LCF is only 0.53, this signifies a considerable decline. The short-term coefficients, listed in Appendix Table A10, are positive and significant, suggesting a temporary increase before long-term deterioration occurs. The error-correction term shows that about half of any deviation from equilibrium is corrected within one year.

Table 3
Long-run Baseline ARDL Results (Renewable versus Fossil Models)

Variable	Renewable Model	Fossil Model
ECT(-1)	-0.300 (p = 0.160)	-0.520*** (p = 0.002)
lnGDPPC	5.301 (p = 0.492)	0.334 (p = 0.813)
lnGDPPC²	-0.374 (p = 0.489)	-0.024 (p = 0.802)
RENEW	0.109 (p = 0.197)	not included
FOSSIL	not included	-0.0554*** (p = 0.006)
CREDIT	-0.005 (p = 0.499)	-0.0025 (p = 0.359)
TRADE	-0.006 (p = 0.236)	-0.0041* (p = 0.071)
F-statistic	3.691 (p > 0.10)	4.917
t-statistic	-1.448 (p > 0.10)	-3.392
Adjusted R^2	0.5955	0.5744
*Significance. *** p < 0.01, ** p < 0.05, * p < 0.10.*		

The long-term impact of renewable energy is not statistically significant. However, in the short term, both the current and past coefficients are negative and significant. An increase in the proportion of renewables quickly diminishes the ecological deficit, although this effect does not persist. The size is similar to the fossil short-term effect, but in the opposite direction.

Table 4 displays the NARDL results, in which neither positive nor negative credit shocks have statistically significant long-term coefficients. The Wald test for symmetry yields a p-value of 0.18, so we cannot reject symmetry at conventional levels. However, the signs are opposite where positive shocks decrease LCF, while negative shocks increase it. The Wald test does not reject symmetry at conventional levels (p = 0.18). There is no robust evidence of asymmetric credit effects in this sample.

Table 4
NARDL Asymmetry Results (Credit as Key Novelty)

Variable or Test	Coefficient (Long run)	Std. Error	p-value
CREDIT_pos	-0.00385	0.00316	0.232
CREDIT_neg	0.00758	0.00659	0.259
Wald test ($\beta^+ = \beta^-$)	F = 1.88	not applicable	0.1805

The quantile ARDL estimates in Appendix Table A11 indicate that the short-term effect of renewable energy is not significant at any quantile. Moreover, there is no evidence suggesting the effect varies with the level of ecological deficit. The Fourier ARDL test, shown in Appendix Table A4, also finds no smooth structural breaks beyond the 2016 dummy. The sine and cosine terms are collectively insignificant, and the D2016 dummy itself is not significant in most models.

Table 5 illustrates four scenarios showing that if the renewable share increases gradually (by half a percentage point annually) or at a moderate rate (by 1 percentage point annually), the LCF never reaches the ecological surplus threshold of 1 by 2050. However, with rapid linear growth (two points per year), the threshold is surpassed in 2039. Moreover, a Net Zero logistics pathway, which accelerates to 70 percent renewable energy by mid-century, reaches surplus slightly earlier, in 2037. Therefore, it is clear that gradual shifts from non-renewable to renewable sources may result in the country experiencing a deficit for decades.

Table 5
Scenario Forecasts of Load Capacity Factor (2024–2050)

Year	Slow (+ 0.5 p.p. per year)	Medium (+ 1.0 p.p. per year)	Fast (+ 2.0 p.p. per year)	Net Zero (logistic to 70 percent)
2024	0.336	0.347	0.368	0.325
2035	0.453	0.581	0.837	0.966
2037	0.475	0.624	0.922	1.025 (≥ 1)
2039	0.496	0.666	1.008 (≥ 1)	1.085
2050	0.613	0.901	1.477	1.388

Notes. These forecasts use a long-run renewable energy elasticity of 0.052, derived from the short-run renewable coefficients in Appendix Table A10 (the sum of D(RENEW) and LD(RENEW), scaled to approximate the long-run impact). The slow, medium, and fast scenarios increase the renewable share by 0.5, 1.0, and 2.0 percentage points per year, respectively. The Net Zero pathway follows a logistic S-curve to 70 percent renewable by 2050. These projections are illustrative.

Table 6 summarises the hypothesis tests dothat is not support asymmetry for fossil fuels or credit. Quantile heterogeneity is not supported because renewable energy shows no quantile-dependent effect. However, the forecasting hypothesis is supported, which means only rapid renewable growth can restore ecological balance by the late 2030s.

Table 6
Hypothesis Testing Synthesis - Support Assessment

Hypothesis	Variable(s)	Hypothesized Effect	Key Result	Supported
H_1 (Asymmetry)	Fossil fuel	Asymmetric negative effect	Wald test p = 0.109 (see Appendix Table A12)	No
	Credit	Asymmetric effect (positive decreases LCF, negative increases LCF)	Opposite signs but Wald p = 0.18	No
	Renewable	No long-run effect	Long-run insignificant (p = 0.197)	Yes
H_2 (Quantile)	Renewable	Effect only at moderate deficit levels	No quantile-dependent effect found	No
	Structural breaks	Smooth breaks present	Fourier joint test p = 0.478	No
H_3 (Forecast)	Renewable transition	Fast growth needed for LCF ≥ 1 by 2030s	Fast path reaches 1 in 2039; Net Zero in 2037	Yes

5. Discussion

We began this work with a simple question. Bangladesh has committed to renewable energy and green finance, yet its Load Capacity Factor remains persistently below one. Something is not functioning as expected. Our findings clarify why. This paper concludes that three points emerge from the analysis. First, fossil fuel consumption has a strong negative long-term impact on the Load Capacity Factor, while renewable energy shows no lasting long-term effect. Second, credit asymmetry is not statistically significant, although the opposing signs of positive and negative shocks suggest a pattern. Third, quantile regression indicates that renewable energy's effect does not vary across different levels of ecological deficit. Furthermore, the scenario forecasts clearly demonstrate that only a swift transition to renewable energy can enable Bangladesh to reach ecological surplus by the late 2030s.

First, fossil fuel consumption consistently presents a significant negative effect on the Load Capacity Factor (LCF). The impact is substantial "a 10 percentage point reduction in the share of fossil fuels would increase the LCF by approximately 0.55 units", potentially transforming Bangladesh from a serious deficit to a surplus. This supports the Environmental Kuznets Curve theory that energy-intensive growth damages natural capital, but it also questions the notion that fossil fuels are a necessary stepping stone that eventually pays for itself. The positive coefficients in the short term indicate that fossil energy temporarily boosts the LCF, likely through immediate GDP growth and investments that enhance biocapacity, but the long-term damage surpasses any short-term

benefits. This pattern aligns with findings by Umair et al. (2024) for newly industrialised nations, although our study is the first to demonstrate this for Bangladesh using the LCF measure.

Second, renewable energy shows a puzzling yet instructive pattern. Its short-term coefficients are negative and significant, showing that an increase in the renewable share quickly cuts the ecological deficit. However, the long-term coefficient is not statistically significant. At first, this seems contradictory. The reason is scale: an average renewable share of only 2.4 percent. The historical variation is too limited to accurately gauge a long-term effect. The significant short-term effects demonstrate that renewables are effective when adopted; the insignificant long-term effect suggests they have not yet been adopted widely enough. This aligns with Qamruzzaman (2024), who also identified weak long-term effects of renewable energy in Bangladesh. Our scenario forecasts go further by showing that rapid expansion (≥ 2 percentage points per year) would reveal the long-term benefits. The lack of quantile heterogeneity simplifies policy: ambitious renewable targets are equally beneficial whether the current deficit is severe or mild.

Third, financial development shows that the asymmetric effect is not statistically robust. The Wald test fails to reject the symmetry hypothesis, and high multicollinearity inflates standard errors. Das et al. (2023) found asymmetric credit effects on CO_2 emissions in Bangladesh, but our results for the more comprehensive LCF indicator do not confirm this. The opposite signs of the NARDL coefficients suggest that positive credit reduces LCF, whereas negative credit increases LCF. They imply that credit expansion finances fossil-intensive activities, while credit contraction inadvertently allows ecological recovery. The 2016 sustainable finance guidelines of Bangladesh Bank, represented by the D2016 dummy, show no significant effect. This may indicate delays in implementation or inadequate enforcement rather than policy insignificance.

On the other hand, trade openness has a small but marginally significant negative long-term effect. This supports the pollution haven hypothesis, although the effect size (0.004 per percentage point) is modest compared to that for fossil fuels. The short-term positive coefficient again indicates a temporary income boost.

We acknowledge several limitations in interpreting the findings of this study. The sample size of 49 observations restricts the power of the NARDL and QARDL tests, so these results should be regarded as preliminary. The high multicollinearity between credit and income suggests that we might be underestimating the effects of credit. Reverse causality cannot be fully dismissed, although the ARDL framework with lagged variables reduces the most obvious risks. Our scenario forecasts assume that the elasticity between renewable energy and LCF remains stable as renewables grow well beyond historical levels. Although this is a strong assumption, scenario analysis is inherently illustrative. Within these constraints, the evidence is clear: a swift shift to renewables is essential for Bangladesh to achieve ecological surplus by the late 2030s. Slow change risks locking the country into decades of deficit.

6. Conclusion and Policy Implications

This paper began with a puzzle that Bangladesh has set renewable energy targets and adopted green finance policies, yet its Load Capacity Factor remains consistently below 1. Our findings resolve that puzzle in an unexpected way. Renewable energy does work, but only in the short term and only when its share is very small. The long-term coefficient is insignificant not because renewables are ineffective but because their historical scale has been too low to leave a measurable mark. Fossil fuels, by contrast, have a substantial and consistent negative long-term impact, and the error correction term confirms that this relationship is stable. Financial development does not display a statistically significant asymmetric effect, although the pattern of coefficients indicates that credit allocation plays an important role. There is no evidence of quantile heterogeneity, suggesting that the benefits from renewable sources do not vary across levels of ecological deficit.

The main conclusion is clear that slow renewable growth traps Bangladesh in decades of ecological loss. Only a rapid shift, increasing the renewable share by at least 2 percentage points annually, can raise the Load Capacity Factor above 1 by the late 2030s. This finding challenges linear thinking and demands urgent policy measures.

Policymakers, including various ministries and the Bangladesh Bank, can follow some recommendations. First, the Ministry should mandate an annual increase in the renewable share of at least two percentage points, supported by feed-in tariffs and competitive auctions for solar and wind projects. Secondly, Bangladesh Bank must more rigorously enforce its sustainable finance guidelines, requiring commercial banks to cease lending for new fossil-fuel power plants and to allocate a minimum proportion of credit to renewable energy projects. Third, trade policy should incorporate environmental conditions, such as green import tariffs or subsidies for clean technology imports, to reduce the negative long-term impacts of trade openness. Fourth, the government should establish a

clear target, such as reaching a 70 percent renewable share by 2050 in line with a Net Zero pathway, which our forecasts indicate would restore ecological surplus by 2037.

Future research can expand this study in several ways. First, a longer time series would improve the reliability of NARDL and QARDL estimates and allow for a more detailed analysis of long-term relationships. Second, using disaggregated credit data that distinguishes between green and conventional lending could provide deeper insights into the role of financial development in ecological sustainability. Lastly, comparative studies across South Asian countries could help determine whether Bangladesh's experience reflects a broader regional trend or a country-specific phenomenon. Finally, this paper raises a question for future researchers: "If a feasible renewable transition is economically and technically possible, as our scenarios assume, then why have successive Bangladeshi governments failed to pursue such a path?"

Declarations

Ethical approval

Not applicable.

Consent to participate

Not applicable.

Consent to publish

Not applicable.

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Competing interests

The authors declare no competing interests.

Author Contribution

M.R.M. conceptualised the study, performed data curation, formal analysis, investigation, and methodology, wrote the original draft, and reviewed and edited the manuscript. R.H. assisted with data collection, validation, and manuscript review. M.M.R. conceptualised the study, supervised the research, validated the results, and reviewed and edited the manuscript. All authors reviewed and approved the final manuscript.

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Data availability

The data used in this study are publicly available from the Global Footprint Network and the World Bank World Development Indicators. Replication code will be made available upon reasonable request.

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Figures

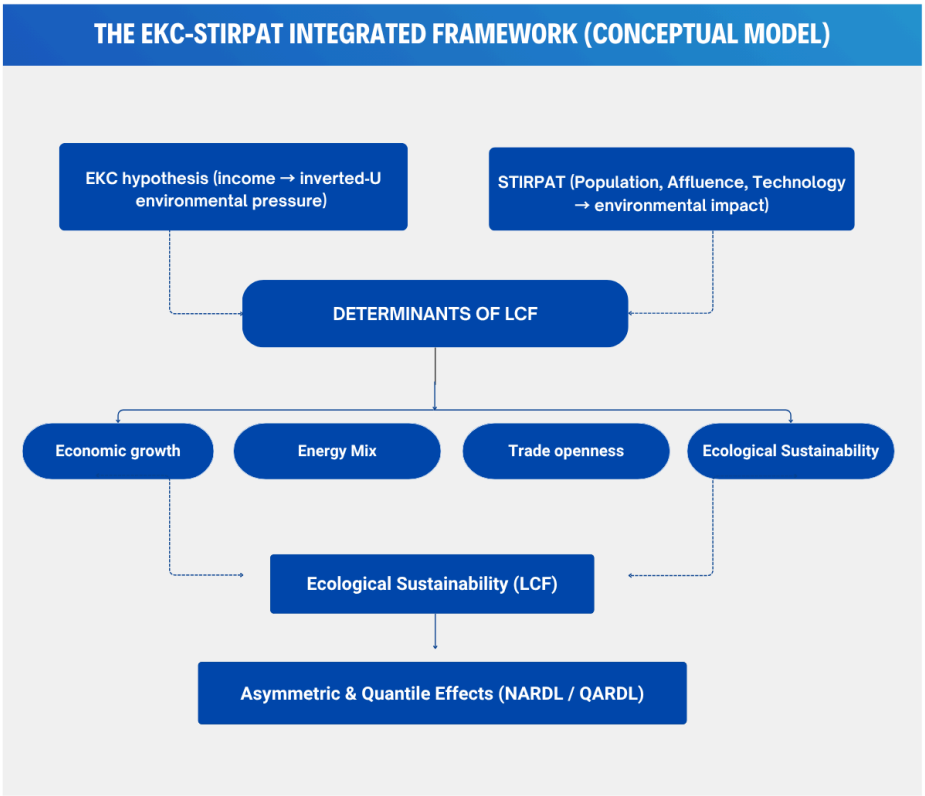


Figure 1

The EKC-STIRPAT Integrated Framework (Conceptual Model)

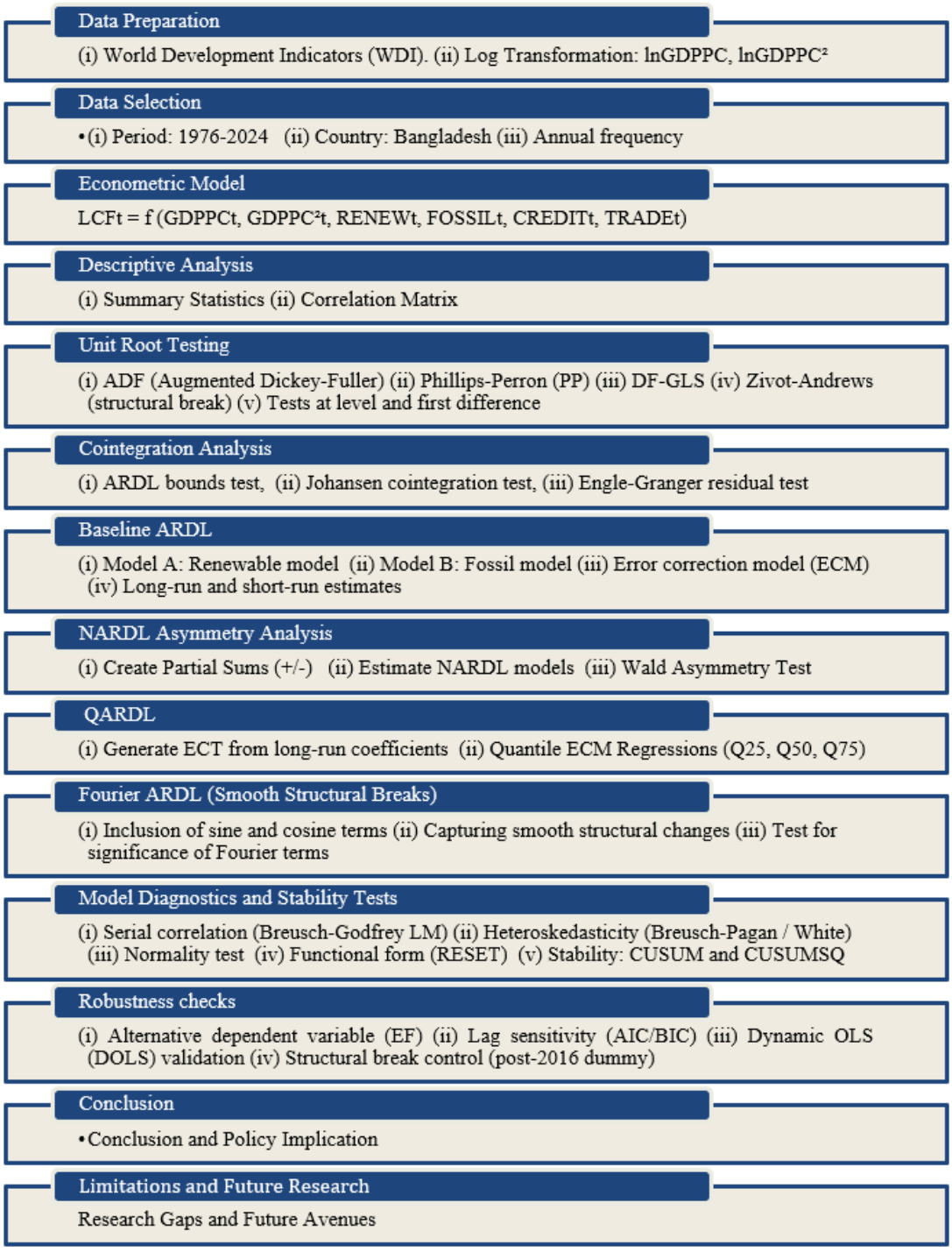


Figure 2

Flow chart of the analytical approaches used in the study (developed by authors)

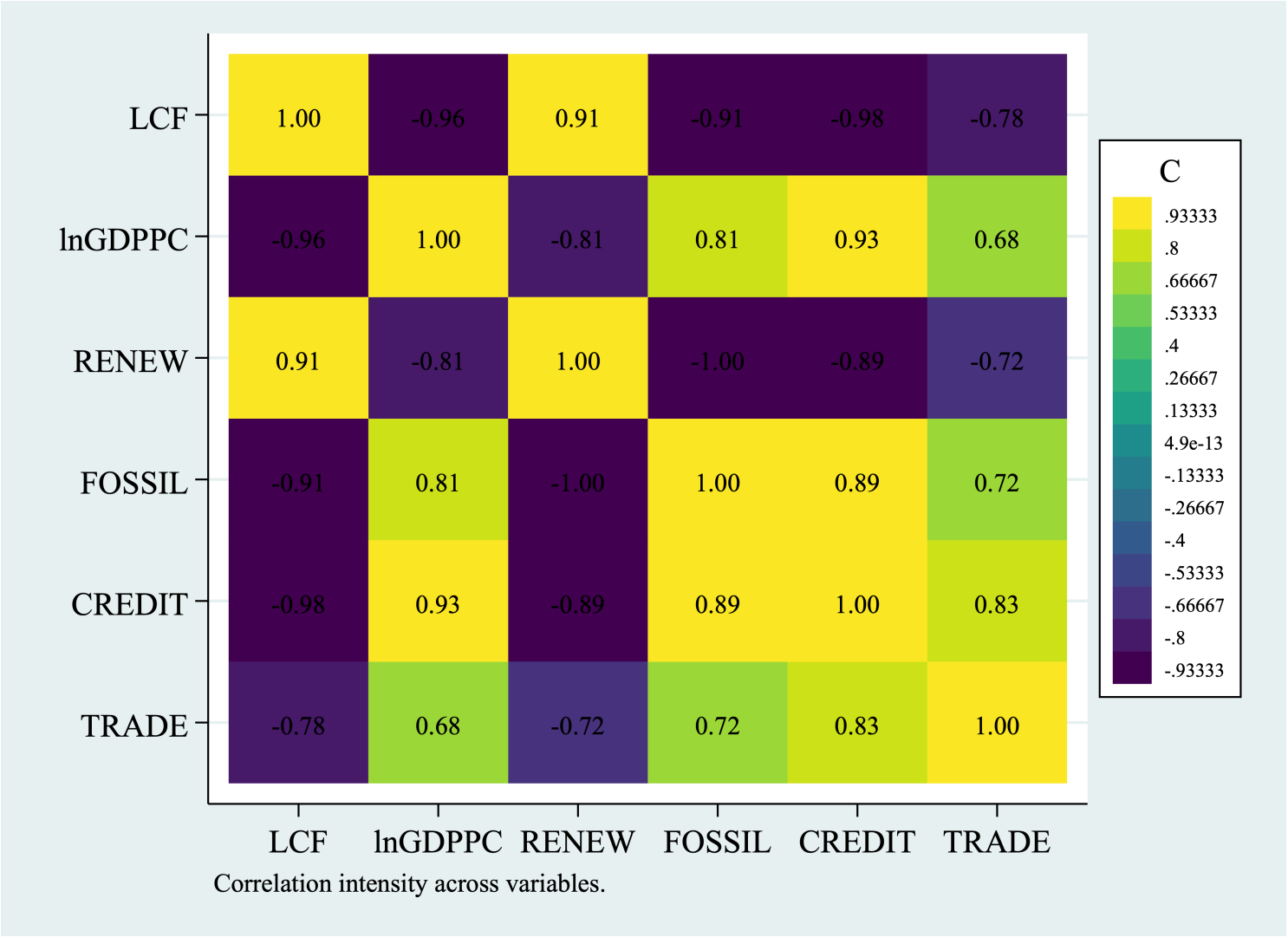


Figure 3

Correlation heatmap of variables.

Source: Author's calculation.
The heatmap confirms strong negative correlations between LCF and GDP, fossil fuel, credit, and trade, while renewable energy shows a strong positive association. The visual intensity highlights the dominance of energy and financial channels in shaping ecological outcomes.

Supplementary Files

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- APPENDIXTABLES.docx