

Energy Transition and Green Innovation: Testing the Load Capacity Curve in Climate-Vulnerable Bangladesh

Abstract

Bangladesh is facing a critical moment due to serious ecological pressure from rapid economic growth, which is driving climate change and environmental degradation. This study examines the determinants of the load capacity factor (LCF) by using annual data from 1990 to 2024. We use ARDL, NARDL, and QARDL models to investigate long-run relationships, asymmetric effects, and state-dependent dynamics. The results yield three core findings for innovation-led green development: (i) renewable energy, a key determinant of ecological sustainability, improves ecological capacity by 1.77% for every 1% increase in renewable energy. (ii) fossil fuel consumption reduces the LCF asymmetrically. A 1% decrease in fossil fuel use improves ecological capacity more than twice as much as a 1% increase harms it. (iii) the relationship between income and ecological sustainability confirms an inverted U-shaped Load Capacity Curve (LCC), but only under high ecological stress (75th quantile). These findings emphasize the urgency of accelerating renewable energy deployment, lessening dependency on fossil fuels, and prioritizing green financial instruments as a central pathway toward ecological sustainability.

JEL: Q43, Q56, C22, O53

Keywords: Load Capacity Factor; renewable energy; fossil fuels; green innovation; ecological sustainability; Bangladesh

22 **1. Introduction**

23

24 Over the past decades, Bangladesh has experienced a rapid transformation into a growing and
25 industrializing economy, often demonstrated as “a rising tiger economy” by doing away with
26 poverty (Uddin et al., 2024). Yet this rapid progress has brought serious environmental pressure.
27 As a consequence, greenhouse gas emissions have boosted up, placing Bangladesh among the
28 countries most exposed to climate hazards and environmental damage (Hasan et al., 2025; Ghosh
29 et al., 2024). A stark and complex reality is faced by Bangladesh; the country must keep on its
30 economic growth, persist within ecological limits, and at the same time respond to deep climate
31 vulnerability. Hence, a sophisticated “triple bind” has been generated by this scenario.

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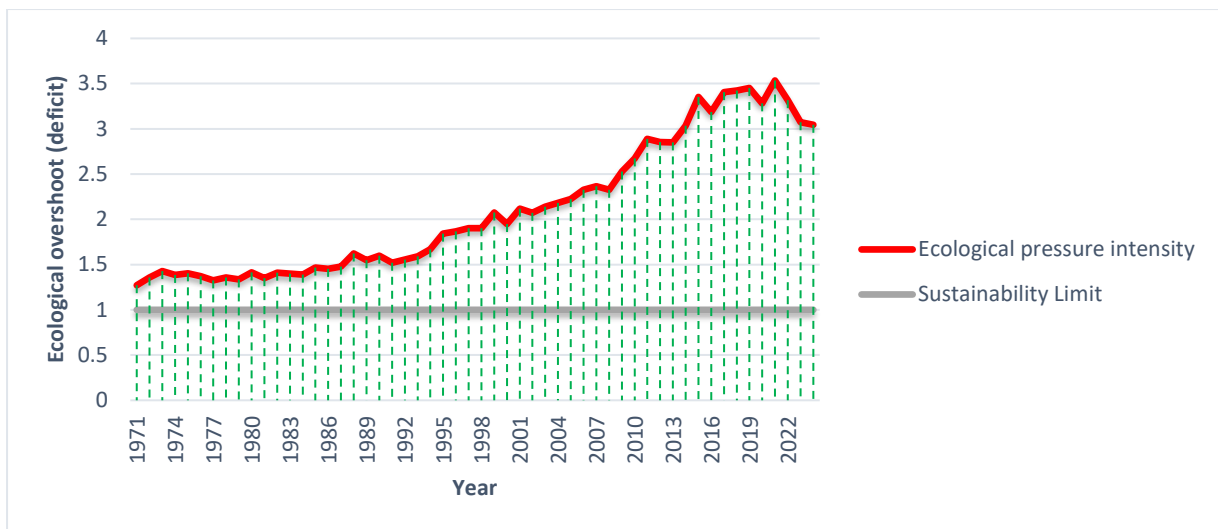
33 A more comprehensive measurement of environmental sustainability is required to identify these
34 challenges. Traditional indicators such as CO₂ emissions capture only segment of the problem.
35 In spite of the focusing on pollution by them, the balance between human demand and nature’s
36 ability to regenerate is disregarded by them. The Load Capacity Factor (LCF) offers a broader
37 and more meaningful measure. Due to this reason, tracing the forces that impact LCF is requisite
38 for depicting effective sustainability policies in a rapidly growing economy like Bangladesh.

39

40 Despite growing interest in sustainability, the current literature leaves several important
41 questions remain unanswered in the literature. First, there is a paucity of comprehensive
42 empirical assessment of Bangladesh’s Load Capacity Factor (LCF) as a unified measure of
43 ecological sustainability. Second, earlier studies have not scrutinized whether financial
44 development and energy consumption affect ecological limits in an asymmetric way when
45 evaluated through a boundary-based indicator such as the LCF. Third, little is known about
46 whether these relationships switch when ecological deficit conditions become more severe.

47

48 The central research question is straightforward: how do financial development, energy
49 transition, and structural change collectively affect Bangladesh’s Load Capacity Factor? More
50 specifically, this study addresses three main questions. First, does Bangladesh exhibit an inverted
51 U-shaped Load Capacity Curve? Second, do positive and negative changes in financial
52 development and fossil fuel use affect the Load Capacity Factor (LCF) in different ways? Third,
53 do these effects vary across different levels of ecological deficit within the LCF distribution? A
54 deeper and more nuanced understanding than traditional linear models is provided by this
55 combined approach, using yearly data from 1990 to 2024.



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57

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Fig. 1 presents the ecological pressure intensity.

59

60 Figure 1 illustrates the initial assessment of the ecological condition of Bangladesh. The
 61 ecological pressure intensity is calculated by dividing the ecological footprint by the biocapacity.
 62 Ecological pressure is the inverse of the Long-term Carrying Capacity (LCF) and represents the
 63 degree of demand imposed on ecosystems relative to their capacity to fulfill it. An ecological
 64 pressure intensity value greater than 1 ($LCF < 1$) implies an ecological overshoot and therefore
 65 indicates the degree to which the demand for resource use exceeds the carrying capacity of
 66 ecosystems.

67

68

69 **2. Literature Review**

70 **2.1 Scope and formation of the review.**

71 The goal of the review is to synthesize the empirical studies that examine the factors of
 72 environmental sustainability. Particular attention has been given on the Load Capacity Factor
 73 (LCF) as a key indicator. Priority is given on research that connects environmental outcomes
 74 with key variables of economic development. Financial growth, the transformation to renewable
 75 energy, trade openness and structural development by urbanization and industrialization are
 76 incorporated in the key factors. Bangladesh and the wider Asian region are given the geographic
 77 focus because fast growth and environmental pressure exist there simultaneously. The early
 78 1990s to the present is captured in the literature because this time period demonstrates deep
 79 globalization, growing energy demand and rising global concern about climate change.

80

81 **2.2 Time-series evidence from single countries, focusing on Bangladesh.**

82 Many studies use time-series economic models to understand both the long-term and short-term
83 environmental impacts in different countries, and Bangladesh frequently appears in these
84 analyses. Usually, the ARDL model and its nonlinear version, NARDL, are applied. Most
85 findings suggest that economic growth, industrial expansion, and fossil fuel use are driving up
86 carbon emissions in Bangladesh, which in turn is harming environmental quality (Hasan et al.,
87 2025; Golder, 2021). However, most of these studies focus only on CO₂ emissions. This gives
88 only a partial picture because it overlooks the balance between the overall ecological demand
89 and supply.

90
91 The impact of economic development is a bit more complex. Some research shows that if
92 regulatory systems aren't strong enough, expanding credit, trade openness, and foreign
93 investment can actually harm the environment (Qamruzzaman, 2023; Kor & Qamruzzaman,
94 2023). Other studies point out that positive and negative financial shocks affect emissions
95 differently (Das et al., 2023; Kibria et al., 2021).

96
97 On the brighter side, renewable energy brings some hope. Using cleaner energy sources can
98 lower emissions and improve environmental conditions (Murshed et al., 2021; Qamruzzaman,
99 2024). Recently, research has started applying the LCF framework directly. For instance,
100 Fourier-based models show that renewable energy and trade openness can improve LCF,
101 although the effect of foreign investment is still mixed (Qamruzzaman, 2024).

102 **2.3 Panel evidence from Asian and global country groups.**

103 Numerous studies use panel data that spanning two or more countries to get a wider view, and
104 the research is usually on the Asian, South Asian, or global samples. There is evidence to back
105 up the hypothesis of the Environmental Kuznets Curve (EKC) hypothesis, which implies that
106 the relationship between income and environmental degradation is inverted-U, and this trend is
107 observed in most Asian economic settings (Nosheen et al., 2019; Chowdhury, 2024). The results
108 of the panel also validate the varying roles of energy sources, in the sense that renewable energy
109 can positively affect the quality of the environment, but non-renewable energy and industrial
110 activity only negatively impact it (Rahman and Alam, 2022; Liu and Lin, 2024).

111
112 The impacts of financial development are diverse in panel studies. LCF is expected to be
113 enhanced in the case of financial growth in the presence of robust institutions (Latif and Faridi,

114 2023), but other studies have determined that financial expansion may lead to higher energy
115 consumption and emissions by industries (Haider and Adil, 2019). The transition into finance
116 and energy also has an environmental impact influenced by moderating factors (e.g.,
117 globalization, regional trade agreements, and institutional quality) (Rani et al., 2022; Liu and
118 Lin, 2024). Heterogeneity and cross-sectional dependence are typically considered with the
119 application of such advanced estimators as System GMM, CS-ARDL, and panel quantile
120 regression (Latif and Faridi, 2023; Wang et al., 2024).

121 **2.4 Emerging nonlinear approaches and new explanatory factors**

122 Recent studies transcend the linear assumptions and the traditional environmental variables.
123 Nonlinear models, which include panel smooth threshold regression, quantile-on-quantile
124 regression, and dynamic panel threshold models, indicate threshold effects and dissimilar
125 reactions under various economic conditions. Such research indicates that the influence of
126 finance, energy transitions, and other aspects on the environment is contingent on structural
127 settings (Yildirim et al., 2025; Majeed and Hussain, 2022; Celik and Guris, 2025). Taking the
128 case of renewable energy, the environmental benefits of renewable energy can be affected by the
129 intensity of the energy in a given country (Yildirim et al., 2025).

130
131 The theoretical base of sustainability is also widened in the literature. Besides, additional factors
132 of explanations, such as geographical hazards, uncertainty in economic policies, technological
133 innovation, artificial intelligence, and digital finance, are being progressively incorporated in the
134 environmental models (Khan et al., 2024; Kartal et al., 2025; Abdulla et al., 2024; Bakhsh et al.,
135 2023). This captures an increasing attempt to find a meaning of sustainability in the complicated
136 global economy.

137 In spite of such developments, there are still gaps. Multi-country panel-based evidence on most
138 nonlinear effects is available, whereas single-country research, especially on South Asia (as with
139 Bangladesh), is sparse. There are limited studies that synergistically investigate the asymmetric
140 impacts of financial growth and energy transformation under one model or use a broad
141 biophysical measure such as LCF. These gaps are essential to climate-sensitive economies in the
142 process of emerging economies, in which the knowledge of interactions between ecological
143 constraints, energy systems, and financial structures is crucial in policy formulation.

144 **2.5 Research gaps and connection to the present study**

145 The objective of bringing these strands together a place is to focus on several undetermined
146 issues. First of all, there exists a methodological gap. Advanced nonlinear methods are found as

147 common in panel analysis and developed-country contexts. But the it is occasionally used to a
148 single growing country like Bangladesh. Second, there persists an integrative gap. Financial
149 development, energy transformation or structural alteration are explored separately more than
150 modeling their combined effects on a comprehensive indicator like LCF. Third, there is a
151 variable gap in understanding how interaction is made between domestic financial framework
152 and policy formulation and energy transformation with a view to designing environmental
153 sustainability in Bangladesh. A number of studies have given contradictory findings concerning
154 the environmental impact of financial development and energy use. As an example, it is advised
155 that environmental sustainability is supported by financial development in terms of green
156 investment and technological development (Qamruzzaman, 2023). Contrastingly, it is believed
157 that financial growth can raise environmental stressors by promoting credit-based industrial
158 operations and fossil-consumption (Das et al., 2023). On the same note, although it is presented
159 the positive impacts of renewable energy implementation on the environment (Murshed et al.,
160 2021), other researchers conclude that its potential is determined by the quality of institutions
161 and the intensity of energy (Yildirim et al., 2025). These contradictions indicate that the effect
162 of the environment can be different in country-specific situations and nonlinear relationships,
163 which should be investigated more through the learning of the sophisticated econometric
164 methods of Bangladesh.

165 The gaps are responded directly by the present study. The work contributes to the ecological
166 sustainability in Bangladesh by merging financial development and energy transition with a
167 nonlinear framework. These are fit to the context of Bangladesh to discover asymmetric and
168 dynamic bonding. More significantly, it combines financial growth, renewable energy
169 transformation and structural economic movement within a unified structure. It interprets
170 variations in LCF. Sharper evidence is offered by this approach on whether those variables
171 conflict or can be aligned to ensure sustainable development.

172

173 **3. Theory and Conceptual Framework**

174 Understanding how Bangladesh can expand its economy without damaging its ecological base
175 requires a clear theoretical foundation. Importantly, this research employs together three
176 complementary theories to form an integrated framework, not only rely on a single perspective.
177 Combining these ideas allows a deeper analysis of the “triple bind” faced by Bangladesh,
178 economic growth, environmental limits, and climate vulnerability (Murshed et al., 2021).
179 Bangladesh is a very topical example of studying these dynamics. The interplay between

180 financial growth, energy transition, and environmental sustainability is a good case to be
181 analyzed in Bangladesh due to this combination of economic growth, the development of energy
182 policy, and its vulnerability to climate change.

183 **3.1 Foundational theories**

184 **3.1.1 Ecological economics and planetary boundaries**

185 This study is based on ecological economics. Ecosystems provide resources and waste
186 absorption to the economies of each country; that is, each nation is restricted by its biocapacity
187 or potential to regenerate what it uses. This balance is embodied in the Load Capacity Factor
188 (LCF) that compares ecological footprint to biocapacity, which is used to determine whether
189 economic activity is within environmental constraints (Latif and Faridi, 2023). An LCF of less
190 than one ($LCF < 1$) is an indication of an ecological deficit, in which the use of resources
191 surpasses the ability of the ecosystems to replenish them.

192 **3.1.2 Endogenous growth, finance, and structural change**

193 The endogenous theory of growth describes the causes-and-effect relationship between the long-
194 term development in an economy due to internal economic causes, with emphasis on financial
195 development, accumulation of capital, and advancement in technology. The financial sector
196 plays an important role in financing industry, infrastructure, and innovation in the rapidly
197 changing economy of Bangladesh (Uddin et al., 2024). Nevertheless, financial growth may have
198 a two-fold impact. The channel of credit-pollution hypothesizes that higher credit levels can
199 stimulate production and consumption of carbon-intensive products and services, aggravating
200 the environmental performance (Qamruzzaman, 2023; Das et al., 2023). On the other hand, the
201 green-finance channel facilitates efficiency, cleaner technologies, and renewable energy (Jui &
202 Saha, 2024). The dominant pathway is related to the policy design and the institutional quality
203 (Latif and Faridi, 2023). Land use, energy demand, and emissions are also transformed due to
204 structural change, including urbanization, industrialization, and a falling agricultural proportion,
205 which affect ecological pressure in Bangladesh (Hasan et al., 2025).

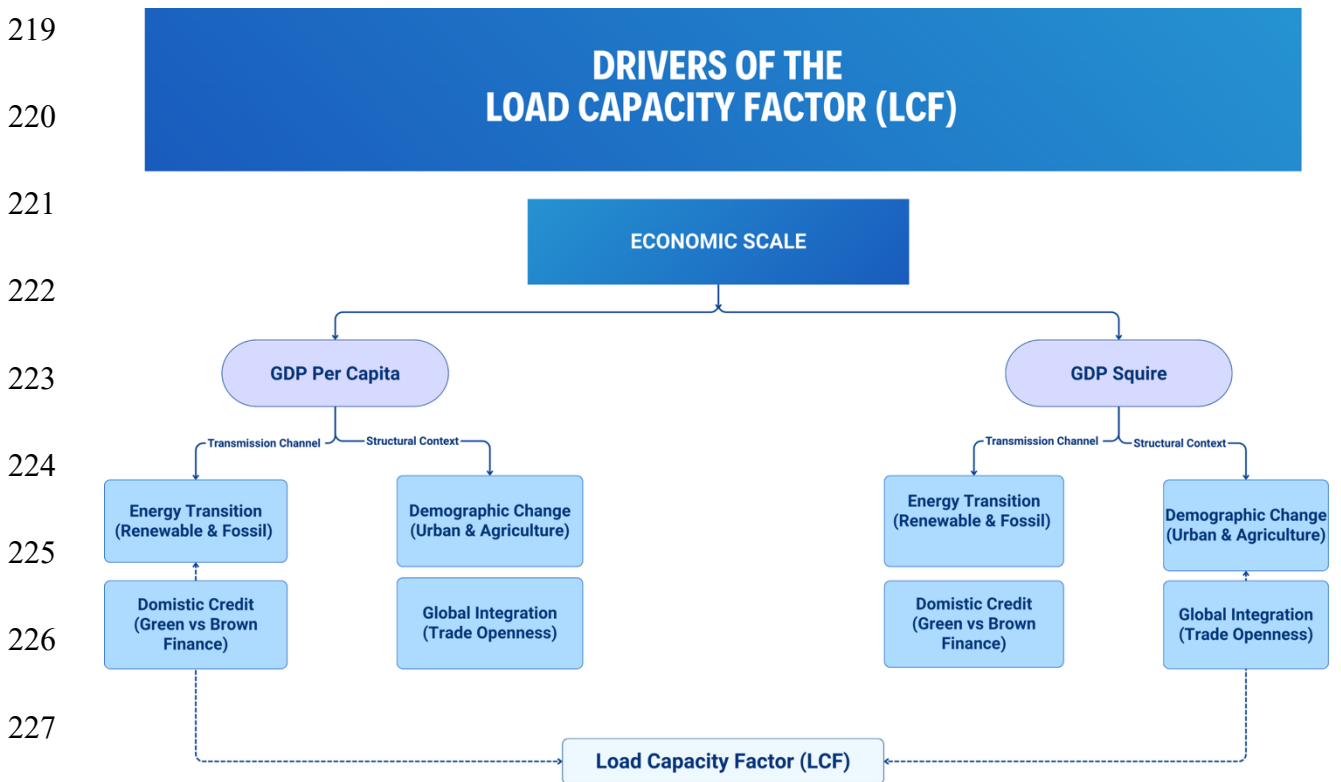
206 **3.1.3 Energy transition and the changing energy base**

207 The energy transition theory analyzes the transition of fossil fuels to renewable energy. In the
208 case of Bangladesh, with increasing energy demand, this shift is critical in climate as well as
209 development planning. Fossil fuels will always be the major emitters and ecological pressure,
210 and renewable energy is an opportunity to achieve a cleaner development and better

211 environmental indicators (Murshed et al., 2021; Qamruzzaman, 2024). The balance between
 212 fossil and renewable energy in the national mix is one of the crucial factors contributing to
 213 ecological sustainability due to policy constraints and the presence of infrastructure and
 214 investment needs that create inertia.

215 **3.2 Synthesized conceptual framework**

216 Bringing these theories together allows the construction of an integrated framework for
 217 analyzing Bangladesh’s Load Capacity Factor, as shown in figure 2, which illustrates the
 218 interconnected drivers and transmission channels.



228 Fig. 2. Conceptual framework of ecological sustainability drivers

229 In this study, one of the hypotheses is the hypothesis of the Load Capacity Curve (LCC), which
 230 is the extension of the Environmental Kuznets Curve, according to which the inverse-U
 231 relationship between income and the Load Capacity Factor (LCF) is observed (Wang et al.,
 232 2024). Growth in early developments might reduce the ecological capacity; however, past a
 233 point, the level of growth can improve the quality of the environment. Structural composition is
 234 subject to interaction with economic scale: urbanization has concentrated consumption and
 235 waste, creating increased ecological pressure, and the agricultural share has a direct impact on
 236 land use and biological regeneration.

237

238 These dynamics are affected by two important channels of transmission. To start with, energy
239 transition, which is recorded in the balance between the use of renewable and fossil energy:
240 renewable energy will diminish ecological pressure, and fossil fuels will only increase it. Second,
241 financial channels, quantified by domestic credit, may contribute towards increased
242 environmental degradation through financing of fossil-based industry or maintain sustainability
243 through renewable energy and technological modernization. The trade openness also links
244 Bangladesh to international flows of production and technology, which may become a source of
245 more environmental pressure due to the pressure on resources, but may also open access to
246 cleaner technologies (Liu and Lin, 2024).

247
248 The effect of these channels is presumably time-dependent. According to the ecological
249 resilience theory, the reaction of LCF to economic or financial shocks is determined by the
250 closeness of the system to environmental boundaries. With a high ecological deficit, extra
251 pressures may cause capacity to plummet when a disproportionate decline in capacity occurs
252 instead of a gradual one.

253 **3.3 Research hypotheses**

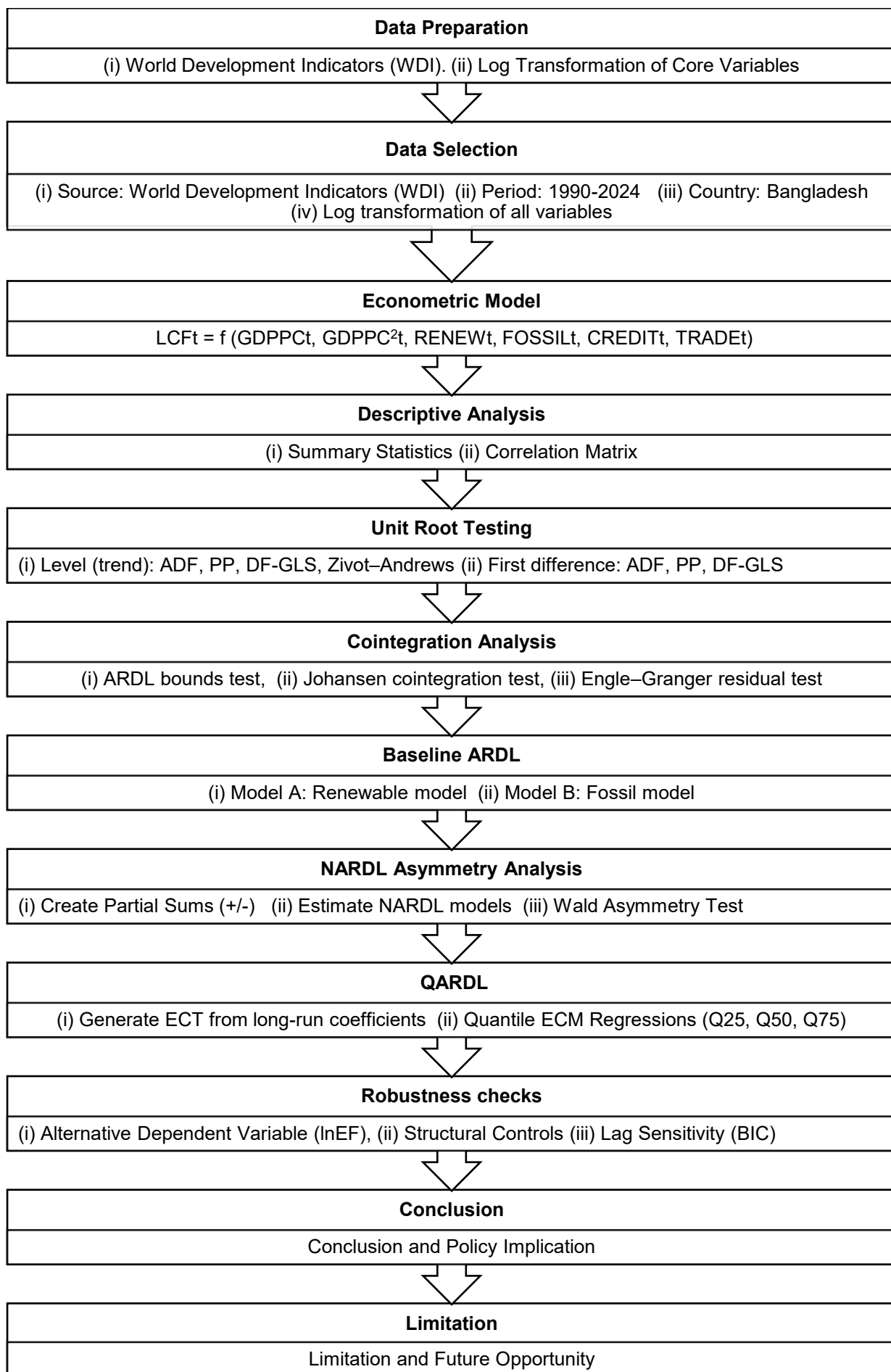
254 Based on this framework, several testable hypotheses are proposed. H₁: Load Capacity Curve
255 hypothesis. GDP per capita and LCF follow an inverted U-shaped relationship in Bangladesh.
256 Economic growth initially reduces ecological capacity, but after a threshold level of income,
257 further growth improves it. H₂: Asymmetric financial effects. Changes in domestic credit affect
258 LCF asymmetrically. Increases in credit are expected to worsen ecological conditions more
259 strongly than decreases improve them, reflecting the persistence of credit-financed activities. H₃:
260 Asymmetric energy effects. Fossil fuel consumption exerts a stronger negative effect on LCF
261 than the positive effect generated by renewable energy. Reductions in fossil use may not produce
262 immediate ecological gains because of structural and infrastructural lock-in. H₄: Conditional
263 (quantile) effects. The strength of these relationships varies across ecological conditions.
264 Financial development and energy transition may influence LCF differently when ecological
265 deficit is severe compared with when it is moderate.

266

267 **4. Methodology**

268 **4.1 Research design and approach**

269 Figure 3 illustrates the analytical approaches used in the study. This study employs a quantitative
270 time-series research design to examine the determinants of Load Capacity Factor (LCF). The
271 Nonlinear Autoregressive Distributed Lag (NARDL) model and the Quantile Autoregressive
272 Distributed Lag (QARDL) approach are two complementary econometric methods. Correlation
273 analysis and descriptive statistics, firstly, establish the basic properties of the data. Secondly, the
274 order of integration for each variable is defined by the unit root tests. Thirdly, cointegration tests
275 verify the existence of long-run equilibrium relationships. Fourth, baseline ARDL models
276 estimate long-run elasticities. Fifth, NARDL models test for asymmetric effects of financial
277 development and energy consumption. Sixth, QARDL models that focus whether these
278 relationships vary across different levels of ecological deficit or not. Finally, diagnostic tests and
279 robustness checks confirm the validity of the findings.



281 Fig. 3. Flow chart of the analytical approaches used in the study.

282 4.2 Study area and variable construction

283 Bangladesh is located in South Asia and is characterized by a low-lying deltaic geography
284 formed by the Ganges–Brahmaputra–Meghna River system. The country is widely recognized
285 as one of the most climate-vulnerable nations in the world due to its high exposure to floods,
286 cyclones, sea-level rise, and riverbank erosion. Rapid economic growth and industrial expansion
287 have increased energy demand, leading to rising pressure on ecological systems. Figure 4
288 illustrates the geographic location of Bangladesh within South Asia. Because this study relies on
289 national-level time-series data, the entire territory of Bangladesh is considered as the study area.



306 Fig. 4. Geographic location of Bangladesh (Study Area) within South Asia.
307 Source: Authors' illustration using MapChart.

309 The study uses annual time-series data for Bangladesh from 1990 to 2024. This time span
310 captures rapid economic transformation together with growing environmental pressures (Uddin

311 et al., 2024; Hasan et al., 2025; Qamruzzaman, 2024). Data sources are the World Development
 312 Indicators (WDI) and the Global Footprint Network (GFN) The dependent variable: the Load
 313 Capacity Factor (LCF), defined as the ratio of biocapacity per capita to ecological footprint per
 314 capita and computed as:

$$315 \quad LCF_t = \frac{BC_t}{EF_t}$$

316 *Where, LCF_t = Load Capacity Factor BC_t = Biocapacity per capita and EF_t = Ecological Footprint*
 317 *per capita*

318 Bangladesh exhibits a persistent ecological deficit ($LCF < 1$) throughout the sample period (Latif
 319 & Faridi, 2023; Wang et al., 2024). The independent variables of the study are selected according
 320 to the theoretical framework, where economic growth is measured by GDP per capita, with its
 321 squared term included to test the Load Capacity Curve hypothesis (Wang et al., 2024).
 322 Renewable and fossil fuel energy consumption capture the energy transition as shares of total
 323 energy use (Murshed et al., 2021; Qamruzzaman, 2024). Domestic credit proxied financial
 324 development to the private sector (% of GDP) (Latif & Faridi, 2023; Kor & Qamruzzaman,
 325 2023). Trade openness is measured by the sum of exports and imports relative to GDP (Rahman
 326 & Alam, 2022). Structural change is represented by urbanization rate and agriculture value added
 327 (Hasan et al., 2025; Uddin et al., 2024). All variables except GDP² are transformed into natural
 328 logarithms for elasticity interpretation (Qamruzzaman, 2023). Table 1 summarizes all variables,
 329 definitions, and data sources.

330 **Table 1: Variable definitions and data sources**

Variable	Definition	Source
lnLCF	Log of Load Capacity Factor (biocapacity / ecological footprint)	Global Footprint Network
lnGDPPC	Log of GDP per capita (constant 2015 US\$)	World Development Indicators (WDI)
lnGDPPC_sq	Square of log GDP per capita	Authors' calculation
lnRENEW	Log of renewable energy consumption (% of total energy)	WDI
lnFOSSIL	Log of fossil fuel energy consumption (% of total energy)	WDI

Variable	Definition	Source
lnCREDIT	Log of domestic credit to private sector (% of GDP)	WDI
lnTRADE	Log of trade openness (% of GDP)	WDI
URBAN	Urban population (% of total population)	WDI
AGRI	Agriculture value added (% of GDP)	WDI

331

332 4.3 Preliminary tests

333 4.3.1 Descriptive statistics and correlation

334 To understand the distributions of all the variables the descriptive statistics are calculated.
 335 Likewise, to examine basic relationships and check for potential multicollinearity pairwise
 336 correlation coefficients are computed. To formally assess multicollinearity, Variance Inflation
 337 Factors (VIFs) are calculated after regression estimation. Following established practice, a VIF
 338 value exceeding 5 indicates problematic multicollinearity that may require corrective action such
 339 as variable transformation or removal (Gujarati & Porter, 2009).

340 4.3.2 Unit root tests

341 To determine the order of integration, we apply the Augmented Dickey-Fuller (ADF) test, the
 342 Phillips-Perron (PP) test, and the Dickey-Fuller Generalized Least Squares (DF-GLS) test, which
 343 has higher statistical power in small samples size. To account for structural breaks, the Zivot-
 344 Andrews test is also employed. This test facilitates for a single unknown break in the trend
 345 function and tests the null hypothesis of a unit root against trend stationarity with a break.

346 4.3.3 Structural break identification

347 According to the Zivot-Andrews test findings and documented policy shifts in Bangladesh, a
 348 structural break dummy variable (D_{2016}) is constructed for the year 2016. Renewable energy
 349 adoption and the implementation of Sustainable Development Goals are marked an increased
 350 policy emphasis on this period (Ghosh et al., 2024). In the dummy variable, the value 0 means
 351 years prior to 2016 and 1 means 2016 and thereafter. As an exogenous regressor, it is

352 incorporated in all ARDL and NARDL specifications to account for potential structural changes
 353 in the underlying data-generating process.

$$355 \quad D_{2016} = \begin{cases} 0, & t < 2016 \\ 1, & t \geq 2016 \end{cases}$$

354

356 **4.4 Cointegration analysis**

357 Before estimating dynamic relationships, it is necessary to confirm long-run equilibrium among
 358 the variables. Three complementary cointegration tests are employed to ensure robust inference.

359 **4.4.1 ARDL bounds test**

360 The ARDL bounds testing approach (Pesaran et al., 2001) is the primary method for testing
 361 cointegration. This approach is appropriate regardless of whether variables are I (0) or I (1) and
 362 performs well in small samples. The unrestricted error correction model is estimated, and the
 363 joint significance of lagged level variables is tested. If the F-statistic exceeds the upper bound
 364 critical value, the null hypothesis of no cointegration is rejected. The ARDL model specification
 365 for testing cointegration is:

$$366 \quad \Delta \ln LCF_t = \alpha_0 + \sum_{i=1}^p \beta_i \Delta \ln LCF_{t-i} + \sum_{j=0}^q \gamma_j \Delta X_{t-j} + \delta_1 \ln LCF_{t-1} + \delta_2 X_{t-1} + \psi D_{2016} \\ 367 \quad \quad \quad + \varepsilon_t$$

368 where X is the vector of independent variables, D_{2016} is the structural break dummy, and ε_t is
 369 the error term.

370 **4.4.2 Johansen cointegration test**

371 As a robustness check, the Johansen cointegration test is applied within a vector autoregressive
 372 framework. Both trace and maximum eigenvalue statistics are reported. The Johansen test is
 373 based on the following vector error correction model:

$$374 \quad \Delta Y_t = \Pi Y_{t-1} + \sum_{i=1}^{k-1} \Gamma_i \Delta Y_{t-i} + \Phi D_t + \varepsilon_t$$

375 where Y_t is the vector of endogenous variables, Π is the long-run impact matrix, and D_t contains
 376 deterministic terms.

377 **4.4.3 Engle-Granger test**

378 The Engle-Granger two-step procedure provides an additional robustness check. In the first step,
379 the long-run equation is estimated by ordinary least squares:

$$380 \quad \ln LCF_t = \theta_0 + \theta_1 X_t + \mu_t$$

381 In the second step, the residuals $\hat{\mu}_t$ are tested for stationarity using ADF tests. Stationary
382 residuals indicate cointegration.

383 **4.5 Baseline ARDL model**

384 The ARDL model incorporates GDP per capita and its square to test the Load Capacity Curve
385 hypothesis (H1).

$$386 \quad LDC_t = a_0 + a_1 GDP_t + a_2 GDP_t^2 + a_3 REN_t + a_4 \ln FOSSIL_t + a_5 \ln CREDIT_t + a_6 TRADE_t \\ 387 \quad + \varepsilon_t$$

388 Where LDC_t represents the load capacity factor, GDP_t denotes real GDP per capita, and GDP_t^2
389 captures the nonlinear effect of economic growth. REN_t , $\ln FOSSIL_t$, $\ln CREDIT_t$, and
390 $TRADE_t$ represent renewable energy consumption, fossil fuel consumption, financial
391 development, and trade openness, respectively, while ε_t denotes the error term.

392 The ARDL approach captures both short-run dynamics and long-run equilibrium relationships
393 within a single framework. The long-run relationship is specified as:

$$394 \quad \ln LCF_t = \alpha_0 + \alpha_1 \ln GDP_t + \alpha_2 \ln GDP_t^2 + \alpha_3 \ln RENEW_t + \alpha_4 \ln CREDIT_t \\ 395 \quad + \alpha_5 \ln TRADE_t + \psi D_{2016} + \nu_t$$

396 The error correction term is constructed as:

$$\begin{aligned}
397 \quad & \Delta \ln LCF_t \\
398 \quad & = \beta_0 + \sum_{\{i=1\}}^{\{p\}} (\beta_{1i} \Delta \ln LCF_{\{t-i\}}) + \sum_{\{i=1\}}^{\{q\}} (\beta_{2i} \Delta \ln GDP_{\{t-i\}}) \\
399 \quad & + \sum_{\{i=1\}}^{\{q\}} (\beta_{3i} \Delta \ln RENEW_{\{t-i\}}) + \sum_{\{i=1\}}^{\{q\}} (\beta_{4i} \Delta \ln FOSSIL_{\{t-i\}}) + \sum_{\{i=1\}}^{\{q\}} (\beta_{5i} \Delta \ln CREDIT_{\{t-i\}}) \\
400 \quad & + \sum_{\{i=1\}}^{\{q\}} (\beta_{6i} \Delta \ln TRADE_{\{t-i\}}) + \lambda_1 \ln LCF_{t-1} + \lambda_2 \ln GDP_{t-1} + \lambda_3 \ln RENEW_{t-1} \\
401 \quad & + \lambda_4 \ln FOSSIL_{t-1} + \lambda_5 \ln CREDIT_{t-1} + \lambda_6 \ln TRADE_{t-1} \\
402 \quad & + \varepsilon_t
\end{aligned}$$

403 In this specification, Δ represents the first difference operator, while i denotes the lag length. The
404 coefficients capture the short-run dynamics among the variables, whereas the lagged level
405 variables represent the long-run equilibrium relationship between load capacity factor and its
406 determinants.

$$\begin{aligned}
408 \quad & ECT_{t-1} = \ln LCF_{t-1} - \hat{\alpha}_0 - \hat{\alpha}_1 \ln GDP_{t-1} - \hat{\alpha}_2 \ln GDP_{t-1}^2 - \hat{\alpha}_3 \ln RENEW_{t-1} \\
409 \quad & - \hat{\alpha}_4 \ln CREDIT_{t-1} - \hat{\alpha}_5 \ln TRADE_{t-1} \\
407 \quad &
\end{aligned}$$

410 where ECT_{t-1} is the error correction term and λ measures the speed of adjustment toward long-
411 run equilibrium. A negative and statistically significant λ confirms convergence to the long-run
412 equilibrium.

413 Two baseline ARDL models are estimated. The first includes renewable energy consumption,
414 financial development, and trade openness. The second replaces renewable energy with fossil
415 fuel consumption. Both include the structural break dummy for 2016. Urbanization and
416 agriculture value added are introduced only in the robustness analysis (Section 4.8).

417 **4.6 Nonlinear ARDL (NARDL) model**

418 The NARDL framework directly tests the asymmetric hypotheses (H2 and H3) derived from
419 credit market imperfection and path dependency theories. This approach decomposes
420 explanatory variables into positive and negative partial sums, allowing increases and decreases
421 to have different effects. For each variable of interest, the positive and negative partial sums are
422 constructed as:

$$423 \quad In\ CREDIT_t^+ = \sum_{j=1}^t \max(\Delta InCREDIT_j, 0)$$

$$424 \quad In\ CREDIT_t^- = \sum_{j=1}^t \min(\Delta InCREDIT_j, 0)$$

$$425 \quad In\ FOSSIL_t^+ = \sum_{j=1}^t \max(\Delta InFOSSIL_j, 0)$$

$$426 \quad In\ FOSSIL_t^- = \sum_{j=1}^t \min(\Delta InFOSSIL_j, 0)$$

427 Here, $In\ CREDIT_t^+$ and $In\ CREDIT_t^-$ denote the cumulative positive and negative changes in
 428 domestic credit, while $In\ FOSSIL_t^+$ and $In\ FOSSIL_t^-$ show the positive and negative change in
 429 fossil fuel energy consumption. As a result, the model is able to capture potential asymmetric
 430 effects of increases and decreases in the explanatory variables on environmental sustainability.

$$431 \quad POS_t = \sum_{j=1}^t \Delta X_j^+ = \sum_{j=1}^t \max(\Delta X_j, 0)$$

$$432 \quad NEG_t = \sum_{j=1}^t \Delta X_j^- = \sum_{j=1}^t \min(\Delta X_j, 0)$$

433 The long-run NARDL relationship is specified as:

$$434 \quad \ln\ LCF_t = \beta_0 + \beta_1^+ POS_t + \beta_1^- NEG_t + \beta_2 Z_t + \psi D_{2016} + \mu_t$$

435 where Z_t represents control variables that are not decomposed. In addition to analyze how the
 436 correlation between variables differs across different conditional distributions of environmental
 437 sustainability, the QARDL model is employed as:

$$438 \quad \Delta InLCF_{t-1} = \gamma_0 + \sum \gamma_{1i} \Delta InLCF_{t-i} + \sum \gamma_{2i} \Delta InCREDIT_{t-i}^+ + \sum \gamma_{3i} \Delta InCREDIT_{t-i}^-$$

$$439 \quad + \sum \gamma_{4i} \Delta InFOSSIL_{t-i}^+ + \sum \gamma_{5i} \Delta InFOSSIL_{t-i}^- + \theta_1 InLCF_{t-1} + \theta_2 InCREDIT_{t-1}^+$$

$$440 \quad + \theta_3 InCREDIT_{t-1}^- + \theta_4 InFOSSIL_{t-1}^+ + \theta_5 InFOSSIL_{t-1}^- + \varepsilon_t$$

441 This nonlinear ARDL framework is extended by the specification of positive (the superscript
 442 notation +) and negative (the superscript notation -) partial sums of the explanatory variables,
 443 which enable the estimation of asymmetric short-run (SR) and long -run (LR) effects of financial
 444 development and fossil fuel consumption on the LCF.

445 The error correction form of the NARDL model is:

$$\begin{aligned}
446 \quad \Delta \ln LCF_t &= \alpha_0 + \sum_{i=1}^p \rho_i \Delta \ln LCF_{t-i} + \sum_{j=0}^q (\pi_j^+ \Delta POS_{t-j} + \pi_j^- \Delta NEG_{t-j}) \\
447 \quad &+ \sum_{k=0}^r \phi_k \Delta Z_{t-k} + \theta_1 \ln LCF_{t-1} + \theta_2^+ POS_{t-1} + \theta_2^- NEG_{t-1} + \theta_3 Z_{t-1} \\
448 \quad &+ \psi D_{2016} + \varepsilon_t
\end{aligned}$$

449 Three NARDL models are estimated, decomposing: (1) Renewable energy consumption (2)
450 Fossil fuel consumption, and (3) Financial development. The Wald test evaluates the null
451 hypothesis of long-run symmetry ($\theta_2^+ = \theta_2^-$) and short-run symmetry ($\sum \pi_j^+ = \sum \pi_j^-$) against the
452 alternative of asymmetry. Bounds testing is also applied within the nonlinear framework to
453 confirm cointegration.

454 4.7 Quantile ARDL (QARDL) model

455 The QARDL model operationalizes the prediction from ecological resilience theory (H4) that
456 the impact of economic drivers on LCF varies across different states of ecological pressure. This
457 approach extends the ARDL framework to allow parameter estimates to vary across quantiles of
458 the dependent variable distribution (Çelik & Güriş, 2025; Wang et al., 2024). The QARDL model
459 is written as:

$$\begin{aligned}
460 \quad Q_{\Delta \ln LCF}(\tau | F_{t-1}) \\
461 \quad = \alpha(\tau) + \sum_{i=1}^p \beta_i(\tau) \Delta \ln LCF_{t-i} + \sum_{j=0}^q \gamma_j(\tau) \Delta X_{t-j} + \lambda(\tau) ECT_{t-1} + \varepsilon_t(\tau)
\end{aligned}$$

462 Where $Q_{\Delta \ln LCF}(\tau | F_{t-1})$ is the τ -th conditional quantile of $\Delta \ln LCF$ given information
463 set F_{t-1} , and all coefficients vary with τ .

464 In order to examine whether the LR relationship varies across different conditional quantiles of
465 environmental sustainability (distributional heterogeneity), the LR QARDL model specification
466 can be approached as like:

$$467 \quad Q_{\ln LCF_t}(\tau) = \mu(\tau) + \sum_{i=1}^p \theta_i(\tau) \ln LCF_{t-i} + \sum_{j=0}^q \beta_j(\tau) X_{t-j} + \varepsilon_t(\tau)$$

468 Where $Q_{\ln LCF_t}(\tau)$ represents the conditional quantile function of the LCF, while the $\mu(\tau)$ shows
469 the quantile specific intercept term, and $\theta_i(\tau)$ is coefficient of the dependent variable, $\beta_j(\tau)$
470 measures the impact of the explanatory variable X_t on environment sustainability. The model
471 illustrates the relationship between X_t and the sustainability of environment in terms of different

472 points of the conditional distribution of the LCF, thus capturing the likely heterogeneity and
473 asymmetric effects across quantiles.

474 Following standard practice, three quantiles are estimated: the 25th percentile (relatively better
475 ecological conditions), the 50th percentile (median), and the 75th percentile (more severe
476 ecological deficit). The error correction term from the linear ARDL model captures the speed of
477 adjustment at each quantile. The quantile-specific long-run coefficients are derived as:

$$478 \quad \hat{\theta}(\tau) = -\frac{\hat{\lambda}(\tau)^{-1}}{1 + \sum_{i=1}^p \hat{\beta}_i(\tau)} \times \left(\sum_{j=0}^q \hat{\gamma}_j(\tau) \right)$$

479 Confidence intervals for the quantile coefficients are obtained through bootstrapping with 500
480 replications.

481 **4.8 Diagnostic tests and robustness checks**

482 To ensure the reliability of the estimated relationships, a series of post-estimation diagnostic tests
483 are conducted. Serial correlation is examined using the Breusch-Godfrey LM test,
484 heteroskedasticity is assessed through the Breusch-Pagan test, and model specification is
485 evaluated using the Ramsey RESET test. These procedures verify that the estimated models
486 satisfy standard econometric assumptions that inference is not driven by misspecification or
487 residual dependence. To further assess robustness, the baseline ARDL model is re-estimated
488 under four alternative specifications.

489 **4.8.1 Alternative dependent variable: ecological footprint**

490 The baseline ARDL model is re-estimated using the logarithm of ecological footprint (lnEF) as
491 the dependent variable:

$$493 \quad \Delta \ln EF_t = \alpha_0 + \sum_{i=1}^p \beta_i \Delta \ln EF_{t-i} + \sum_{j=0}^q \gamma_j \Delta X_{t-j} + \lambda ECT_{t-1} + \psi D_{2016} + \varepsilon_t$$

492

494 Where X includes $\ln\text{GDPPC}$, $\ln\text{GDPPC}^2$, $\ln\text{RENEW}$, $\ln\text{CREDIT}$, and $\ln\text{TRADE}$. This
495 specification tests whether the determinants of environmental pressure differ from those of
496 ecological sustainability.

497 **4.8.2 Additional structural controls**

498 Urbanization (lnURBAN) and agriculture value added (lnAGRI) are incorporated into the ARDL
 499 framework to account for demographic and sectoral transformation. The error-correction
 500 representation becomes:

$$501 \quad \Delta \ln LCF_t = \alpha_0 + \sum_{i=1}^p \beta_i \Delta \ln LCF_{t-i} + \sum_{j=0}^q \gamma_j \Delta X_{t-j} + \sum_{k=0}^r \delta_k \Delta Z_{t-k} + \lambda ECT_{t-1} + \psi D_{2016} + \varepsilon_t$$

502 where Z denotes lnURBAN and lnAGRI. This extension verifies whether the core coefficients
 503 remain stable after controlling for structural shifts.

504 **4.8.3 Alternative lag selection (BIC)**

505 The baseline ARDL specification is re-estimated using the Bayesian Information Criterion
 506 (BIC), allowing a maximum of two lags. The model structure remains identical to the baseline
 507 ARDL specification described in Section 4.5. This procedure confirms that the main findings are
 508 not sensitive to the chosen lag order.

509 **4.8.4 Dynamic Ordinary Least Squares (DOLS)**

510 As an alternative long-run estimator, Dynamic Ordinary Least Squares (DOLS) is employed to
 511 correct for potential endogeneity and serial correlation (Stock & Watson, 1993). The
 512 specification is:

$$514 \quad \ln LCF_t = \theta_0 + \theta_1 \ln GDP_{PC,t} + \theta_2 \ln GDP_{PC,t}^2 + \theta_3 \ln RENEW_t + \theta_4 \ln CREDIT_t$$

$$515 \quad + \theta_5 \ln TRADE_t + \sum_{j=-1}^1 \phi_j \Delta X_{t+j} + \psi D_{2016} + \mu_t$$

513
 516 where X represents the vector of independent variables. One lead and one lag of the first-
 517 differenced regressors are included to preserve degrees of freedom given the limited sample size.

518

519 **5. Results and Discussion**

520
 521 The empirical findings are reported in a rational order in this section. It starts with the descriptive
 522 statistics and correlation analysis, then unit root and structural break results, and finally the
 523 cointegration testing. Next, the discussion of the baseline ARDL estimates, asymmetric NARDL

524 results, quantile ARDL analysis, robustness checks, and diagnostic testing is given. In every
 525 section, there is an explanation of the economic significance of the results and the policy
 526 implications.

527 **5.1 Descriptive Statistics and Correlation Analysis**

528
 529 Table 2 provides the summary statistics of the variables. The average value of lnLCF is (-0.878),
 530 which means that Bangladesh has been at an ecological deficit ($LCF < 1$) during the period 1990-
 531 2024 years. The comparatively small range indicates that the ecological pressure is long-lasting
 532 as well as structural and not cyclical or temporary. This trend speaks of the historical unequal
 533 distribution of demand on the ecological and biocapacity. The consumption of renewable energy
 534 (lnRENEW) is more variable than the consumption of fossil fuel (lnFOSSIL), a slow but bumpy
 535 process of the energy transition. The financial development (lnCREDIT) and trade openness
 536 grow as time passes, which is expected with the financial deepening and its higher integration as
 537 it becomes globalized.

538
 539 Table 3 shows strong correlations between lnLCF and lnRENEW (0.985), lnFOSSIL (-0.959),
 540 and lnGDPPC (-0.955). Such trends indicate that energy structure can be more conclusive on
 541 ecological sustainability as opposed to income growth. Variance inflation factors are not critical,
 542 and this means that multicollinearity is not a threat to the estimation reliability.

543

544 **Table 2: Variable definitions and summary statistics**

Variable	Definition	Obs.	Mean	Std. Dev.	Min	Max
lnLCF	Log of Load Capacity Factor (biocapacity / ecological footprint)	35	-0.878	0.268	-1.263	-0.418
lnGDPPC	Log of GDP per capita (constant 2015 US\$)	35	6.774	0.448	6.160	7.571
lnGDPPC _s q	Square of log GDP per capita	35	—	—	—	—
lnRENEW	Log of renewable energy consumption (% of total energy)	32	3.832	0.338	3.219	4.292

lnFOSSIL	Log of fossil fuel energy consumption (% of total energy)	26	4.102	0.154	3.798	4.315
lnCREDIT	Log of domestic credit to private sector (% of GDP)	35	3.363	0.362	2.677	3.793
lnTRADE	Log of trade openness (% of GDP)	35	3.433	0.251	2.939	3.874
URBAN	Urban population (% of total population)	35	26.276	3.931	19.864	32.678
AGRI	Agriculture value added (% of GDP)	35	18.933	6.008	11.004	31.677

545
546 Notes: Annual data, 1990–2024. GFN = Global Footprint Network; WDI = World Development
547 Indicators. Descriptive statistics for lnGDPPC² are not separately reported as it is a deterministic
548 transformation of lnGDPPC.

549

550 **Table 3**
551 **Correlation matrix and variance inflation factors**
552 **Panel A. Correlation matrix**

	lnLCF	lnGDPPC	lnRENEW	lnFOSSIL	lnCREDIT	lnTRADE
lnLCF	1.000					
lnGDPPC	-0.955***	1.000				
lnRENEW	0.985***	-0.997***	1.000			
lnFOSSIL	-0.959***	0.942***	-0.955***	1.000		
lnCREDIT	-0.945***	0.867***	-0.903***	0.969***	1.000	
lnTRADE	-0.598***	0.448***	-0.535***	0.595***	0.783***	1.000

Panel B. Variance inflation factors (renewable model)

Variable	VIF
lnGDPPC	8.12
lnRENEW	7.36

lnCREDIT	4.53
lnTRADE	2.86

Notes: *** $p < 0.01$. VIF for lnGDPPC² not reported due to deterministic collinearity with lnGDPPC.

553 5.2 Unit Root and Structural Break Results

554

555 The findings of the ADF, PP, and DF-GLS unit root test are presented in Table 4. None of the
556 variables is stationary, but on first differencing, they become stationary. This indicates that the
557 series is of the order of one, I (1). Not all the variables are integrated to order two, which is the
558 main requirement to use the ARDL approach. It is crucial to mention that the Zivot–Andrews
559 test identifies structural breaks occurring in different years across variables, including 1996,
560 1998, 2016, and 2019, indicating heterogeneous structural shifts in Bangladesh’s
561 macroeconomic and environmental dynamics. No statistically significant break is detected for
562 fossil fuel consumption. The break in 2016 coincides with the expansion of sustainable finance
563 guidelines and increased policy emphasis on renewable energy development in Bangladesh
564 (Bangladesh Bank, 2021; Millat, n.d.). The 2016 break is accompanied by the increased policy
565 effort in the areas of sustainable finance and promotion of renewable energy.

566 **Table 4**

567 Unit Root Results

Variable	ADF (Level)	PP (Level)	DF-GLS (Level)	ZA break	ADF (Δ)	PP (Δ)	DF-GLS (Δ)	Order
lnLCF	-0.081	-1.149	-1.525	2019	-2.502	- 7.037*	-2.478**	I (1)
lnGDPPC	-2.520	-2.350	-1.587	1996	-1.558	-2.986	-0.888	I (1)
lnRENEW	-1.593	-2.045	-1.468	1998	- 4.060*	- 4.663*	-2.781*	I (1)
lnFOSSIL	-2.646	-1.321	-2.505	—	-1.538	- 5.048*	-2.561	I (1)
lnCREDIT	0.080	0.071	-1.022	2016	- 2.801*	- 5.812*	-3.111*	I (1)
lnTRADE	-1.151	-1.080	-1.123	2016	-3.136	- 5.074*	-4.556*	I (1)

568 Notes: ***, **, * denote significance at 1%, 5%, and 10%. No variable is I (2).

569

570 5.3 Cointegration Analysis

571 Finding the long-run relationships requires first ensuring that the variables are moving together
 572 in the long run. The ARDL gives the F-statistic (6.457), which is greater than the upper critical
 573 value (at 5% level), and therefore the null hypothesis (F-statistic of 6.457) is rejected. Both the
 574 Johansen trace test and the maximum eigenvalue test are positive indications that there exists a
 575 single cointegrating variable. The Engle-Granger test is further evidence. The uniformity of the
 576 results of methods enhances the belief in the presence of a constant long-run equilibrium between
 577 ecological capacity, income, energy structure, financial development, and openness to trade. This
 578 observation suggests that ecological sustainability is not impacted by changes in energy and
 579 financial structure in the short term.

580

581 **Table 5**
 582 **Cointegration tests**

Test	Statistic	5% critical value	Decision
ARDL bounds F	6.457	4.707	Cointegrated
Johansen trace	96.346	68.52	1 CE
Johansen max-eigen	58.189	33.88	1 CE
Engle-Granger Z(t)	-4.387	-5.269	Significant at 10%

583

584 Notes: CE = cointegrating equation.

585 **5.4 Baseline ARDL Results**

586

587 Table 6 shows the long and short-term ARDL estimates using two specifications: (a) With
 588 renewable energy, and (b) With the use of fossil fuel. The error-correction terms are negative
 589 and statistically significant in both models (-0.731 and -1.117). These coefficients affirm that it
 590 goes towards the long-run equilibrium. The magnitudes are relatively huge, implying quick
 591 adjustment after the short-run deviations, signifying the high correlation between the economic
 592 activity and ecological capacity. There is a high positive long-run impact of renewable energy
 593 consumption on LCF. The 1.767 coefficient ($p < 0.01$) suggests that an increase in the use of
 594 renewable energy by 1 percent increases ecological capacity by 1.77 percent. The elasticity of it
 595 surpasses unity which implies that there is a high level of ecological value that is derived from
 596 renewable investment. The outcome is a confirmation of the ecological modernization theory, as

597 well as it provides a primary role to clean energy in enhancing the sustainability outcomes.
 598 Conversely, the use of fossil fuels prominently diminishes the ability of the ecology. The -0.838
 599 ($p < 0.01$) coefficient proves that fossil dependence still destroys the ecological balance. The
 600 scale indicates the cost of the structural environment of the fossil-intensive growth.

601
 602 The Load Capacity Curve hypothesis receives partial empirical support. The inverted U-shaped
 603 income trend is also only present in the fossil specification and with weak statistical support.
 604 This implies that economically motivated ecological enhancement is not natural. Rather, it is a
 605 matter of relying on the underlying energy structure. There are no statistically significant direct
 606 impacts of financial development and trade openness. This points out that the aggregate financial
 607 growth can be ecologically neutral unless distribution of credit between sustainable sectors is
 608 altered. Financial deepening and growth alone are hence not sufficient to recover ecological
 609 balance without changing its structure through energy transition.

610

611 **Table 6**

612 **Baseline ARDL long-run estimates**

Variable	Renewable model	Fossil model
lnGDPPC	-3.287 (2.937)	4.610* (2.265)
lnGDPPC ²	0.272 (0.213)	-0.357** (0.161)
lnRENEW	1.767*** (0.542)	—
lnFOSSIL	—	-0.838*** (0.229)
lnCREDIT	0.340 (0.275)	-0.153 (0.129)
lnTRADE	-0.042 (0.093)	—
ECT	-0.731*** (0.170)	-1.117*** (0.250)
Observations	31	25
R ²	0.715	0.589

613 Notes: Standard errors in parentheses. Dependent variable: $\Delta \ln \text{LCF}$. Diagnostic tests indicate no
 614 serial correlation, no heteroskedasticity, and parameter stability.

615

616 **5.5 NARDL Asymmetry Results**

617

618 Table 7 shows the asymmetric long-run effects of the NARDL estimated model. There is a
 619 massive imbalance that arises in the consumption of fossil fuels. The null of symmetry is rejected

620 with the Wald test ($F = 13.92, p < 0.01$). LCF is increased by a large percentage (1.742) when
621 there is a decrease in the use of fossil fuels and decreased by a lesser percentage (-0.781) when
622 there is an increase. It implies that the ecological benefits of fossil phase-down are not
623 proportionately high. The outcome is in line with the path-dependency and lock-in theories,
624 which imply that the sustainability gains of breaking fossil dependence would be multiplied. On
625 the other hand, renewable energy impacts are not asymmetrical. The Wald test does not reject
626 that there was a similarity between positive and negative change in renewable energy, meaning
627 that there is a proportionate change in renewable energy. The increase in renewable energy is
628 always in a stable, ecologically friendly way. There are no substantial asymmetry and direct
629 long-term effect of domestic credit. The asymmetric impact of domestic credit on ecological
630 sustainability was examined using the NARDL framework. The estimation results show that a
631 positive shock in domestic credit has a statistically significant negative effect on the load
632 capacity factor ($-0.448, p < 0.10$), indicating that credit expansion may increase environmental
633 pressure in Bangladesh. In the contrary, the negative shocks of the coefficient are statistically
634 insignificant (0.004), suggesting a reduction in credit does not produce a measurable effect on
635 ecological sustainability within the sample period. However, the Wald test for asymmetry ($F =$
636 2.06) is statistically insignificant, implying that the null hypothesis of symmetric effects between
637 positive and negative credit shocks cannot be rejected. As a result, it is clear that the Hypothesis
638 H2 is not supported by the formal asymmetry test, though the estimated coefficients indicate
639 differences in magnitude between positive and negative credit shocks. One possible explanation
640 is the relatively small annual sample size (1990–2024), which may limit the statistical power of
641 the Wald test. This supports the conclusion that the composition of credit is important instead of
642 the total amount of lending. These findings underscore the need to hasten the process of depleting
643 fossil fuels and concurrently increase the use of renewable power.

644

645 **Table 7**

646 **NARDL long-run asymmetry**

Variable	Positive shock	Negative shock	Wald F	Decision
Renewable	1.288 (1.002)	1.551*** (0.405)	0.06	Symmetric
Fossil	-0.781** (0.284)	1.742*** (0.592)	13.92***	Asymmetric
Credit	-0.448* (0.242)	0.004 (0.307)	2.06	Symmetric

647 Notes: Wald null hypothesis: $\beta^+ = \beta^-$

648

649 **5.6 Quantile ARDL (QARDL) Results**

650
 651 Table 8 investigates the question of whether relationships vary at levels of ecological deficit with
 652 quantile ARDL estimates of the 25th, 50th and 75th percentile. Renewable energy is positive
 653 and statistically significant in all quantiles with coefficients between 1.113 and 1.163. These
 654 estimates remain stable, implying that renewable energy provides a stable ecological gain
 655 whether the ecological stress is high or low. The extent of the relative similarity of the renewable
 656 energy coefficients of the lower (25th), median (50th) and upper (75th) quantile shows that the
 657 ecological benefits of renewable energy are distributionally neutral within different ecological
 658 deficit regimes. That is, the scale of the environmental amelioration that is linked with renewable
 659 energy is not materially different at low ecological stress and at high ecological deficit. However,
 660 effects of income are state-dependent. The error correction term provides significant values only
 661 at the 75th quantile (-0.469, $p < 0.01$), indicating that the adjustment mechanisms of the long-
 662 run processes are only active when the ecological deficit is severe. The inverted U-shaped pattern
 663 of incomes can also only be observed at the upper quantile. These results are consistent with
 664 ecological resilience theory, which states that system processes increase in the case of
 665 environmental stress. Although renewable investment is positive in any situation, income-
 666 oriented ecological betterment takes place primarily in situations when the ecological pressure
 667 is high.

668

669 **Table 8**

670 **Quantile ARDL estimates**

Variable	Q25	Q50	Q75
ECT_{t-1}	0.192 (0.236)	-0.165 (0.181)	-0.469*** (0.128)
$\Delta \ln GDPPC$	7.756 (13.730)	-7.979 (10.528)	-24.341*** (7.452)
$\Delta \ln GDPPC^2$	-0.493 (0.936)	0.595 (0.718)	1.712*** (0.508)
$\Delta \ln RENEW$	1.113** (0.480)	1.163*** (0.368)	1.127*** (0.261)
$\Delta \ln CREDIT$	-0.043 (0.193)	-0.030 (0.148)	-0.103 (0.105)
$\Delta \ln TRADE$	-0.024 (0.136)	-0.016 (0.104)	0.023 (0.074)
Pseudo R ²	0.351	0.403	0.456

671

672 **5.7 Robustness Checks**

673

674

Table 9 documents some of the robustness tests, such as alternate dependent variables, extra structural controls, alternate lag selection specifications, and DOLS estimation. Renewable energy is positive and statistically significant in all ARDL specifications. With renewable energy as the negative dependent variable and ecological footprint, there is the expected negative sign of renewable energy, and the balance adjustment persists. DOLS also establishes the direction of the relationship but with the small sample size, statistical significance becomes weak.

680

681 **Table 9**

682 **Robustness checks**

Specification	lnRENEW	ECT	Cointegration
Baseline ARDL	1.767*** (0.542)	-0.731***	Yes
+ Structural controls	0.944*** (0.262)	-0.979***	Yes
BIC lag selection	1.314*** (0.409)	-0.809***	Yes
lnEF dependent variable	-0.858 (0.561)	-0.632***	Bounds inconclusive (5%); ECT significant
DOLS	1.162 (0.756)	—	Not applicable

683

684 **5.8 Diagnostic Tests**

685

686 The models are also reliable (Appendix A-E). Serial correlation and heteroskedasticity are not present. RESET tests assist the appropriate functional structure. The residuals are normally distributed, and the CUSUM and CUSUMSQ tests show that the parameters do not change over time. The findings of these results indicate the econometric soundness of the empirical findings.

690 **5.9 Hypotheses Testing Summary**

691

692 This part is a compilation of the results of the ARDL, NARDL, and QARDL models against Hypotheses H1-H4. Table 10 provides a summary of the direction and strength of the results of these complementary methods. The use of renewable energy has a positive and statistically significant long-run relationship with the Load Capacity Factor in all specifications and all quantiles. This recurrent fact proves that it plays the key role in enhancing ecological sustainability and validates previous research on Bangladesh (Murshed et al., 2021;

698 Qamruzzaman, 2024). On the contrary, the consumption of fossil fuel is not asymmetric. The
 699 estimates given by the NARDL indicate that the ecological benefits derived from the cut in the
 700 utilization of fossil fuels which are more than twice the losses incurred by similar increments
 701 (Wald F = 13.92, $p < 0.01$). This result confirms Hypothesis 3, and it is consistent with the path
 702 dependency theory (Shin et al., 2014), which states that the reduction in fossil fuel dependence
 703 is disproportionately beneficial to the environment.

704
 705 The hypothesis of the Load Capacity Curve (H1) is partially confirmed. The anticipated inverted
 706 U-shaped pattern of income would be insignificant in the baseline ARDL estimation, statistically
 707 significant in the QARDL estimation in the 75th quantile, where ecological deficit is highest.
 708 This result, dependent on the state, fits in ecological resilience theory (Celik & Guris, 2025). The
 709 direct effect of financial development on the ecological capacity is not statistically significant in
 710 any of the models, which rejects Hypothesis 2. Nevertheless, the high interrelations between
 711 credit and energy variables indicate that the distribution of credit could be a crucial factor, rather
 712 than its aggregate amount (Das et al., 2023). The quantile analysis also validates Hypothesis 4,
 713 in that the adjustment mechanism and income effects are reinforced due to a high level of
 714 ecological stress, whereas the positive effect of renewable energy is consistent across the board.
 715 Combinedly, the findings suggest that the sustainability of the ecological situation in Bangladesh
 716 depends primarily on the structural shifts in the energy mix and not on the automatic ones.

717 **Table 10: Summary of Hypothesis Testing Results**

Hypothesis	Description	Testing Method	Result
H ₁ (LCC)	Inverted U-shaped relationship between GDP per capita and LCF	ARDL + QARDL	Partially supported
H ₂ (Credit Asymmetry)	Credit increases harm LCF more than decreases help	NARDL	Not supported
H ₃ (Energy Asymmetry)	Fossil fuel effects are asymmetric; renewable effects are symmetric	NARDL	Supported (fossil only)
H ₄ (Quantile Effects)	Relationships vary across levels of ecological deficit	QARDL	Supported

718

719 **6. Conclusion and policy implication**

720 **6.1 Conclusion**

721

722 In this paper, the authors analyze the ecological sustainability determinants in Bangladesh
723 through the Load Capacity Factor (LCF). Findings indicate that renewable energy always
724 increases ecological capacity, whereas the use of fossil fuels weakens it. Ecological benefits of
725 income growth are conditional but not automatic, and monetary development and trade openness
726 impact ecological systems only when they are coupled with sustainable practices.

727

728 This research makes three contributions. Originally, it generalizes state-dependent dynamics on
729 top of the Load Capacity Curve framework by non-translating. Second, it gives country-specific
730 evidence that the energy structure, not income growth, takes center stage in ecological
731 sustainability. Third, it brings to the fore the ecological regulation mechanisms, which present
732 the fact that, rather than passive development, environmental stress and structural change are
733 more significant. These findings require broader comparative and micro-level studies in order to
734 generalize them.

735 **6.2 Policy Implications**

736

737 The study identifies a definite policy response: the ecological sustainability of Bangladesh is
738 heavily reliant on the energy system transformation. Renewable energy always enhances the
739 ecology, and therefore, its fast use is the key element in the planning of national development.
740 Uncertainty can be minimized through measures including increased integration of the grid,
741 simplified approvals, better power purchase agreements, and an investment-friendly
742 environment to develop long-term capital for clean energy development.

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744 It is also critical to reduce the usage of fossil fuels. The marginal ecological benefits of the
745 reduction of fossil fuels are imbalanced, which means that stalling is costly to the environment.
746 The technological lock-in can be averted by a gradual, authoritative phase-down assisted by
747 carbon pricing, a slow removal of unproductive subsidies and incentives towards clean energy,
748 leading to reduced adjustment costs in the future. An increase in the economy does not guarantee
749 ecological balance.

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751 Environmentally, financial development and trade openness seem to be environmentally neutral
752 at the aggregate level, being proximate rather than structural factors. Opportunities can be
753 provided by policies like green taxonomies, environmental disclosure, and financing tools to use

754 credit in renewable and low-carbon industries, and trade policies can help to get access to cleaner
755 technologies and efficient production techniques.

756 **6.3 Limitations and Future Research**

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758 There are a number of limitations to be taken considered. To begin with, the study is about
759 Bangladesh, which does not generalize to other developing economies that may have diverse
760 institutional, financial, or energy backgrounds. Comparative panel design examinations over
761 South or Southeast Asia may evaluate more generalizable applicability. Second, national time
762 series at the macro level could obscure regional/sectoral ecological pressure and energy
763 consumption differences, but in the future, more focused data could be provided by sub-national
764 or sector-level data. Third, unlike the other two sustainability indicators, the Load Capacity
765 Factor is a holistic measure of sustainability that is based on standardized ecological accounting
766 and might include measurement uncertainties. The strength of the results can be challenged by
767 adding more indicators of the environment. Lastly, the present-day model fails to mention the
768 variables of institutional quality, governance, or technological innovation, which may condition
769 the interaction between finance, energy systems, and ecological outcomes. The framework may
770 be extended to these factors in future studies, or threshold effects may be studied, or cross-
771 country panel designs may be used to capture more dynamic relationships. This would bring
772 more insight into the role of structural changes in propelling ecological sustainability in the
773 developing economies.

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Required Declarations

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work, the authors used Grammarly in order to improve language and readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article. The authors did not use any generative AI or AI-assisted technologies in the preparation of this manuscript.

Credit Author Statement

Author 1 Name: Conceptualization, Methodology, Formal analysis, Writing – Original Draft, Visualization.

Author 2 Name: Data curation, Software, Validation, Writing – Review & Editing.

Author 3 Name: Investigation, Resources, Supervision, Project administration.

(Customize roles based on actual contributions. Choose from: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.)

Data Availability Statement

The data that support the findings of this study are available from public sources: Load Capacity Factor data were obtained from the Global Footprint Network (<https://data.footprintnetwork.org>) All other variables were sourced from the World Bank's World Development Indicators (WDI) database (<https://databank.worldbank.org/source/world-development-indicators>). The authors confirm that the data used in this study are publicly available and can be accessed through the repositories cited above. The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

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