



Asymmetric effects of renewable energy, trade, and FDI on environmental sustainability in Bangladesh: Fourier ARDL/NARDL evidence from Bangladesh

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ABSTRACT

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The study assesses how renewable energy consumption (REC), trade openness (TO), and foreign direct investment (FDI) influence environmental sustainability in Bangladesh, using the load capacity factor (LCF) and its inverse (ILCF). It tests the environmental Kuznets curve (EKC), quantifies symmetry and asymmetry, and maps causality over 1990–2022, utilizing annual data from the World Bank, UNCTAD, and IRENA. The analysis employs unit root and cointegration tests, including ADF/Fourier ADF, Perron–Vogelsang, Bayer–Hanck, and Maki. Long-run and short-run estimations are conducted via Fourier ARDL and Fourier NARDL, while causality is examined through Toda–Yamamoto and Fourier (TY) Shock transmission via the TVP-SVAR. Quantile-on-quantile analysis explores state dependence. Results indicate that REC increases LCF and decreases ILCF in the long run, with positive REC shifts yielding larger gains than negative shifts. FDI reduces LCF and increases ILCF, effects that are more significant during inflow surges. TO decreases LCF, and contractions in TO cause larger losses than expansions. The EKC holds with LCF ($Y < 0$, $Y^2 > 0$) and reverses with ILCF. Causality flows from LCF to REC and FDI, and vice versa. The TVP-SVAR shows the increasing roles of REC and TO in LCF variance over time. Quantile-on-quantile estimates reveal larger REC effects in high-REC/high-LCF states and mid-TO quantiles, while FDI effects remain shallow. Error correction terms confirm a stable adjustment to the long-run equilibrium. These econometric insights are relevant for public policy, providing evidence-based guidance for designing adaptive regulatory and investment strategies that balance growth with environmental sustainability.

Contribution/Originality: This study pioneers the application of Fourier ARDL and NARDL models, utilizing the load capacity factor and its inverse, to evaluate the asymmetric effects of renewable energy, trade, and FDI on Bangladesh's environmental sustainability. It provides new empirical evidence linking the EKC framework to policy strategies for sustainable economic development.

1. INTRODUCTION

Bangladesh faces complex development challenges, struggling to balance economic growth and sustainability with the fulfillment of its Sustainable Development Goals (SDGs). Bangladesh is one of the most climate-sensitive nations; however, it accounts for only 0.56 3/4 of global carbon emissions. Environmental pollution (deforestation in particular) leads to substantial financial losses. The price in 2023 was 3.4% of GDP, a significant blow to the state's economy (Rana, Lowe, & Azam, 2023). These issues are aggravated by unsustainable policies that prioritise short-term economic interests over environmental conservation. Even with achievements of alleviating poverty and

implementing sustainability programs, Bangladesh stands in danger. Industrialisation remains predominant in the country and continues to damage the environment (Lau, Choong, & Eng, 2014; Nathaniel, Nwodo, Sharma, & Shah, 2020). There is a stronger link between economic growth and environmental degradation. There are high correlations between industrialization, energy consumption, urbanization, and the increasing emissions of CO₂; it exceeded 98 million metric tons in 2020. The empirical research confirms that pressure on the environment is driven by energy consumption, urbanisation, and openness to trade, and that institutional weaknesses often do not help to curb it Rahman, Hashan, Sharon, and Saha (2024) and Hasan and Chongbo (2020). The ecological footprint increased to 0.68 Global hectares per capita, peaking in 2020-2023, owing to careless resource utilisation. In 2019 and 2022, Bangladesh expanded renewable energy capacity by 1,000 and 1,378 MW, respectively, which are not enough to offset the environmental costs of fossil fuels.

Bangladesh's evidence is consistent with the Environmental Kuznets Curve theory, which posits that environmental degradation increases and later decreases in proportion to rising GDP. GDP and energy consumption in this country have been characterised by rising emissions (Eulerpool, 2023; Pata, 2022). These demonstrate the interdependence of development and ecological health, and demand a radical shift in policy as the economy grows. According to recent statistics, GDP growth, foreign direct investment (FDI), and trade are drivers of emissions. Renewable energy innovations and improved governance can check all these effects. Health is also a victim of environmental degradation: lifespan is reduced by a considerable margin due to CO₂ emissions (Murshed, Ferdous, Rashid, Tanha, & Islam, 2021). Policy makers should strengthen environmental laws, allocate capital to clean technologies, and ensure accountability in government expenditure. In the absence of a disciplined regime and targeted investments in energy, infrastructure, and data acquisition, inequality, sector inefficiencies, and environmental decline will undermine the long-term sustainability of Bangladesh and the realisation of its SDGs. Bangladesh is one of the countries most affected by climate change. It was vulnerable due to its densely populated areas and limited land and water resources. Due to global warming and environmental degradation, climate-related disasters such as floods and cyclones have intensified (Murshed, Elheddad, Ahmed, Bassim, & Than, 2022). The country's territory consists predominantly of low-lying deltaic landscape, covering approximately one-third of the total acreage. They are particularly at risk from sea-level rise and extreme weather, which could jeopardise people's quality of life and financial well-being. Economic progress triggers intensive industrialisation and urbanisation, leading to severe environmental issues such as air and water pollution, deforestation, and biodiversity loss. The government recognises the need to switch to renewable energy to mitigate environmental impacts and enhance energy security (Marques & Caetano, 2020). Fossil fuels can be replaced with renewable energy sources that do not produce greenhouse gases that pollute the environment. The incorporation of sustainability in economic policymaking will be able to stabilise the development objectives and harmonise them with those of the United Nations SDGs, sustainable energy, and climate action.

FDI plays a role in ensuring environmental sustainability in Bangladesh. FDI can also help generate renewable energy projects and facilitate clean development by providing capital and technology (Munjer, Hasan, Hossain, & Rahman, 2023). Research indicates a positive direct relationship between FDI and GDP increase, and governments emphasise their role in several SDGs and clean infrastructure (Haque, Chowdhury, & Rashid, 2023). FDI injections are important because environmental harm from dirty investments that exploit lower environmental standards can be aggravated (Sutradhar, 2020). Bangladesh will be a target for attracting FDI, thereby compromising its environmental targets (Hanif, Uddin, Bakirtas, & Kader, 2023). Environmental conditions are also affected by trade openness. Although trade can improve productivity and provide access to clean technology, liberalisation without controls can be counterproductive (Antweiler, Copeland, & Taylor, 2001; Haseeb, Xia, Saud, Usman, & Quddoos, 2023; Huilan, Akadiri, Haouas, Awosusi, & Odu, 2024; Okelele, Lokina, & Ruhinduka, 2022). The trade-environmental sustainability linkage is complex, as trade can lead to environmentally friendly technology transfer, while resource extraction and pollution can result if environmental standards are not maintained (Contribution of Tax-Induced

Foreign Direct Investment for Sustainable Development in Bangladesh). Hence, Bangladesh needs sustainable trade policies and measures to promote economic growth without compromising environmental health. According to recent macro fundamentals.

Transformative change in these large-scale systems requires new thinking about environmental sustainability in Bangladesh. Existing measures, such as carbon intensity and ecological footprint, capture only limited information. LCF and its inverse (ILCF) were used as indicators of ecological sustainability in this study. While LCF compares the ratio of actual use to biocapacity by resource, ILCF turns this comparison around and measures stress. The combined use of such indicators can determine whether economic activities are detrimental or gainful to ecological capacity. This study considers Bangladesh for the first time using these indicators. It can test whether income also evolves systems as follows: the EKC - the inverted-U relation between emissions and income (emissions increase at low per-capita incomes of groups within society, but decrease when they exceed some threshold, which possibly exists but has been disputed for less-developed countries).

This study uses the Fourier expanded ARDL and nonlinear ARDL models. These methods are applied to both symmetric and asymmetric effects. They enable the decomposition into positive and negative changes in renewable energy consumption, trade openness, and FDI. They also allow for structural breaks and non-linear trends, two factors that were previously overlooked in studies. Therefore, this investigation compensates for this lack of method and provides more valid access to relations in movement.

The contributions of this study are as follows. The first purpose is to assess the impact of renewable energy consumption on LCF and ILCF in Bangladesh. It is whether renewables add to ecological capacity and take away less. The second aim is to investigate the impact of trade openness and FDI on LCF and ILCF. There are two competing hypotheses regarding a possible positive relationship between trade: integrated trade may encourage green growth through technology exchange, while crisp export-induced growth may exacerbate environmental pressure. The paper further examines the direction of the spillover effect, depending on whether the FDI is of high quality (clean) or low quality (dirty). Third, we reexamine the EKC hypothesis using LCF/ILCF and symmetry/asymmetry testing data. However, several questions emerge from the latter goals. The Impact of Renewable Energy Consumption on Load Capacity Factor and Vice Versa in Bangladesh: How Do Trade Openness and FDI Affect the aforementioned Sustainability Indicators? Regarding the degree to which the contributions of RE, T, and FDI affect EC, or not, around 21%. Also, this specific issue remains with these ideas. Is the EKC valid in terms of the LCF and ILCF? What is the impact of environmental capacity on imported renewable energy consumption, trade openness, and FDI? The answers to these questions will help shape policies that balance the region's economic and environmental interests.

The remainder of this paper is organised as follows. Section 2 reviews the relevant literature on the interrelationships between renewable energy consumption, trade openness, foreign direct investment, and environmental sustainability. Section 3 outlines the data sources, theoretical model, and methodological framework, including the use of the Fourier ARDL and Fourier NARDL techniques. Section 4 presents and discusses the empirical findings, highlighting both symmetric and asymmetric dynamics. Section 5 offers a causality and robustness assessment to validate these results. Finally, Section 6 concludes the study by presenting key policy implications and recommendations for promoting environmental sustainability in Bangladesh through strategic energy, trade, and investment measures.

2. LITERATURE SURVEY

2.1. Theoretical Review

The EKC proposition holds that at relatively low-income levels, pollution or environmental stress rises with economic expansion (if any) but then decreases after a turning point, suggesting a U-shaped relationship (Dam & Sarkodie, 2023; Hakkak, Altıntaş, & Hakkak, 2023). The existing literature indicates two relationships between

economic growth and carbon emissions: at low levels of income, the relationship is positive, whereas it becomes negative as income increases, creating an inverted U-shaped pattern (Latif & Faridi, 2023). Another domain of studies indicates an inverted U-dependence of the full or single insurance rate for developed countries, using nonlinear methods, while other studies show an N-shaped relationship in the middle region, and some find an inverse S-shaped curve (Sultana, Rahman, & Khanam, 2022; Wang, Wang, Li, & Jiang, 2024). The EKC provides a departure point for exploring whether Bangladesh's future growth will lead to environmental improvement or whether structural changes and policies are necessary, given the mixed empirical evidence from Bangladesh. Energy consumption and pollution have increased with rapid industrialisation and urbanisation, and the inflexion point predicted by the EKC may not yet have been reached. Thus, the framework employs the EKC as a theoretical benchmark but augments it with additional hypotheses to account for trade and investment effects, as well as ecological capacity.

The pollution haven hypothesis suggests that FDI from rich countries is encouraged (by lax environmental regulation) or discouraged (by strict regulation) in developing nations, providing evidence of the role of FDI in leading to coded pollution havens (Apergis, Pinar, & Unlu, 2023; Cole & Elliott, 2005; Yilanci, Bozoklu, & Gorus, 2020). This has significant implications for Bangladesh, which is seeking investment to expand its industries, and enforcement there is not always as robust. The pollution halo hypothesis offers an opposing perspective, suggesting that multinational enterprises with relatively advanced technologies can transfer cleaner production methods to host countries, thereby decreasing emissions (Apergis et al., 2023; Cole & Elliott, 2005). Some host countries attract FDI from high-technology-firms that can reduce carbon emissions (Hoa, Xuan, Thu, & Huong, 2024; Latif & Faridi, 2023). The pollution haven vs. halo debate in Bangladesh depends on the type of FDI and the strength of environmental legislation. The framework focuses on both because there is a diversity of investors in Bangladesh: some come for lower compliance costs, while others arrive to invest in cleaner manufacturing.

Environmental results can stem from how trade openness affects different pathways of economic growth. More trade can lead to higher incomes, but it can also result in pollution if production expands without sufficient environmental restrictions. "Foreign direct investment is attracted to countries with lax regulations. The studies by Udemba and Yalçıntaş (2021) and Yilanci et al. (2020) examined the relationship between trade liberalization and the pollution haven hypothesis. However, trade is also an engine for spreading cleaner technologies and expanding the efficiency frontier. These competing pathways are represented in the model through trade–environment interactions within a framework. The incorporation of FDI and trade into the model is consistent with Bangladesh's export-led industrialization, particularly in the garment industry. Trade policies must strike a balance between economic gains and environmental losses.

2.2. Environmental Impact of Renewable Energy

For China, the role of RED was investigated using provincial data for the period 2000-2029 to slow the rate of carbon emissions into the environment. According to the study's findings, a beneficial role has been documented during the study period: RED in Chinese provinces alleviates environmental sustainability concerns in the presence of financial development. The study further found that the propensity to include clean energy is significantly higher in provinces with higher pollution intensity (Çakmak & Acar, 2022; Dam & Sarkodie, 2023; Destek & Sinha, 2020). Similar studies focusing on the OECD (Adebayo & Samour, 2024; Ansari, Haider, & Masood, 2021; Azimi & Rahman, 2024) have shown that a 1% increase in RED would lead to a 7.45% increase in CO₂ emissions over the period from 2000 to 2029. Additionally, the literature (Pata, 2022) has shown that beyond developed nations, RED has positively improved environmental quality through ecological sustainability, environmental protection, and national awareness of adopting clean energy in the energy mix. Focusing on Malaises, Saqib, Sharif, Razzaq, and Usman (2023) have shown that beyond developed nations, RED has positively improved environmental quality through ecological sustainability, environmental protection, and national awareness of adopting clean energy in the energy mix. Focusing on Malaises, Saqib et al. (2023) concluded an investigation and found that electricity generation using coal

and gas results in higher CO₂ emissions. According to policy implementation, studies advocate an energy transition from fossil fuels to clean energy because the environmental costs outweigh the benefits. Furthermore, Environmental sustainability, as measured by the ecological footprint in the G7, is the subject of a study by. The study documented that the transition in energy consumption from conventional to renewable sources, especially at the household level, positively accelerates environmental development by restoring ecological stability. Similar results have been reported in the literature (Hakkak et al., 2023; Hasan & Chongbo, 2020; Hoa et al., 2024). The ecological footprint is a more holistic measure of environmental damage, as it identifies where environmental sustainability lies by accounting for the amount of nature required to meet human demand for natural resources. Recent empirical evidence shows that renewable energy can reduce ecological footprints across various geographic locations. An examination implemented by Jaiswal et al. (2022) of the Vietnamese economy between 1986 and 2022 using asymmetric ARDL modelling found that, *ceteris paribus*, a rise in primary energy consumption for renewable resources fell significantly with natural resource demand over the long term, and that fueled consumption was associated with an increased ecological footprint. A similar study conducted by Pata (2022) on G7 countries showed mixed environmental trade-offs: geothermal and hydroelectric energy significantly reduced environmental footprints, whereas biofuel consumption intensified ecological pressure. Based on data from 1990 to 2020 and applying FMOLS and DOLS techniques, Xu et al. (2023) disclosed that a 1% rise in hydropower generation and geothermal power development led to significant reductions (of -0.7483% and -0.2248%, respectively) in ecological footprints, hence supporting the Environmental Kuznets Curve in these economies. The results of the second-generation econometric analysis of the top 25 tourist destination countries indicate that economic growth, renewable energy production, green growth, and environmental innovation are positively correlated, while financial development has an adverse effect. Similarly, Khan et al. (2023) conducted a study on China, India, Indonesia, and Pakistan for the years 1990-2022, employing panel quantile ARDL approaches, and reported stability in the negative relationships between renewable energy consumption and ecological footprint at various quantiles, indicating policy support from renewable energies for sustainable development.

The empirical analysis, see for instance (Ergun & Rivas, 2023; Hoa et al., 2024; Jaiswal et al., 2022), using a cross-sectional autoregressive distributed lag specification on G8 countries during 1990-2018, indicates that renewable energy, technological innovation, and digitalisation all positively promote environmental health, measured by the load capacity factor. The results show that the consumption of green energy can improve biocapacity and mitigate ecological footprints, which demonstrates a positive relationship with the load capacity ratio. Moreover, a study by Raihan et al. (2022) across 26 OECD countries from 1980 to 2018, which employed quantile common correlated effects mean group estimators, demonstrated that human capital, resource rents, and renewable energy increase the load capacity factor, whereas urbanisation reduces ecological quality. Country-based studies conducted by Umair, Yousuf, Ul-Haq, Hussain, and Visas (2023) and Wang, Ge, and Li (2023) using Fourier ARDL and NARDL for the period 1990 to 2022 found that in Bangladesh, renewable energy consumption (REC) and openness of trade positively affect environmental sustainability through load factor capacity enhancement manifested as reduced CO₂ emissions and ecological footprint. The research also yields new findings in environmental economics: environmental quality can be improved through cleaner technologies associated with economic growth. Across the IGAD region, a long-run heterogeneous panel framework analysis has validated that globalisation is powerless, while renewable energy mitigates the ecological footprint and plays a significant role in enhancing load capacity, despite some statistical insignificance in specific models.

2.3. Trade-Environment Nexus

The importance of trade liberalisation for economic growth, capital formation, human capital development, and the mitigation of income inequality has been well documented and widely appreciated (Antweiler et al., 2001; Guo, Meng, Luan, & Wang, 2023; Lu, 2020). Nonetheless, the dark side of TO has also been identified as a significant

concern in ensuring environmental sustainability worldwide, especially in developing nations (Okelele et al., 2022; Udeagha & Breitenbach, 2023). Developing nations are eager to open their economies for the betterment of their nations, but at the cost of environmental degradation. Recent studies, Dam and Sarkodie (2023), Destek and Sinha (2020), and Huilan et al. (2024), indicate that the impact of trade openness on CO₂ emissions differs under different economic conditions. A comprehensive study of emerging countries through 2025 revealed that trade openness exhibits only a slight negative correlation with CO₂ emissions, suggesting substantial heterogeneity in the effects of trade and policy structures on the environment. Nevertheless, this conclusion is in stark contrast to what we know at local levels. In Sub-Saharan Africa, a study analysing 38 countries over the period 2002, 2022 reported that trade openness is significantly associated with increasing CO₂ emissions in the decomposition of CO₂ emissions across the primary (agriculture), secondary (industry), and tertiary (services) sectors.

Similarly, studies on BRICS Plus countries have found that foreign direct investment and trade openness have positive, statistically significant effects on long-term carbon emissions. The difference in effects seems closely related to income and development (Jiaduo, 2023; Yilanci et al., 2020). Furthermore, a study by Apergis et al. (2023) and Zhao, Lin, and Bashir (2024), analysing high-income OECD countries over the last century and a half, revealed direct and indirect influences of openness to trade on emissions. The direct effect indicated a positive relationship between trade openness and CO₂ emissions, while the indirect one, through income growth, was negatively oriented and compensatory. These opposing effects are consistent with the EKC conjecture, indicating that as income levels increase, OE gradually outweighs DE, leading to a long-term reduction in emissions in developed economies. However, evidence from developing countries supports trade openness as a catalyst for environmental degradation, with the study by Guo et al. (2023) and Huilan et al. (2024) using 64 developing countries providing weak support for the pollution haven hypothesis. The impact on the environment, in general (excluding climate change), as measured by the ecological footprint, encompasses land use, water use, and resource depletion beyond carbon emissions. Recent empirical results reveal that trade openness is a strong driver of the ecological footprint in developing and newly industrialised countries. An analysis of ten Newly Industrialised Countries (NICs) from 2003 to 2016, conducted in 2024, revealed that non-green trade openness, encompassing trade flows of non-environmentally friendly goods, leads to environmental degradation through the scale effect. The findings verified that the economy, in the presence of trade liberalisation and market access improvements resulting therefrom, grows alongside the deterioration of its environment, especially when the products exchanged entail high environmental costs (Okelele et al., 2022). This is consistent with the pollution haven hypothesis, which posits that environmental regulation is laxer in countries and areas that attract high-pollution industries from the developed world.

2.4. FDI–Sustainability Interaction

According to the Pollution Halo Hypothesis, green innovation, cleaner technologies, and sophisticated industrial processes may be transferred from developed to developing nations through FDI, thereby reducing environmental degradation (Cole & Elliott, 2005; Hoa et al., 2024; Pata, 2022). This difference is evident from a study of foreign direct investment (FDI) patterns in Morocco from 2010 to 2024. Green FDI, like the NOOR Ouarzazate Solar Complex, decreased sectoral CO₂ intensity by 4.2% for every 10% increase in investment, whereas traditional FDI, like the Tangier Automotive Hub, increased CO₂ intensity by 2.7% for the same investment level. The environmental impacts of foreign direct investment (FDI) are highly sector- and investment-specific, as this variation demonstrates. According to recent cross-country research, various geographical and economic situations affect environmental sustainability in different ways. Foreign direct investment (FDI) results in a 0.354% increase in CO₂ emissions in South Asian nations studied between 1990 and 2022, and a two-way causal relationship exists between FDI and environmental degradation (Latif & Faridi, 2023). While foreign direct investment (FDI) significantly enhances GDP growth in BRICS economies, research employing sophisticated econometric methods, such as Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS), has demonstrated that it also

exacerbates income inequality and environmental degradation. The quality and longevity of foreign investments in developing economies are called into doubt by these results (Musah, 2022; Udemba & Yalçıntaş, 2021; Yilanci et al., 2020). The sectoral mix of foreign direct investment (FDI) is a key factor in determining environmental outcomes. Supporting the pollution haven concept for specific investment corridors, an analysis of OECD and BRICS nations from 2000 to 2003 found that Switzerland, Denmark, and the United Kingdom were major contributors to CO₂ emissions in BRICS nations (Cutcu, Beyaz, Gerlikhan, & Kilic, 2023; Dada & Akinlo, 2021; Murshed et al., 2022). Carbon emissions in the BRICS economies were not considerably affected by foreign direct investment (FDI) from other OECD nations, such as Austria, Finland, Japan, the Netherlands, Portugal, and Switzerland. This suggests that environmental impacts are moderated by investor origin and industry emphasis.

A novel metric for environmental sustainability, the load capacity factor (LCF), considers both the supply (nature's regenerative capacity) and demand (human consumption) sides of the equation by measuring the ratio of biocapacity to the ecological footprint. The LCF footprints consider both the impact of humans on water and air quality, as well as nature's capacity to absorb waste and replenish resources. When LCF diminishes, environmental degradation occurs, making it a particularly sensitive metric of ecological balance (Adebayo, Pata, & Akadiri, 2024; Adebayo & Samour, 2024; Awosusi, Adebayo, Kirikkaleli, Rjoub, & Altuntaş, 2024; Hakkak et al., 2023; Kartal, Pata, Destek, & Caglar, 2023). While foreign direct investment (FDI) and gross domestic product (GDP) tend to worsen environmental degradation, new studies on China's economy from 1979 to 2022 that used Fourier bootstrap autoregressive distributed lag (ARDL) cointegration analysis revealed that urbanization, along with value-added farming, forestry, and fishing, actually improved sustainability in certain regions. The study's findings, which support the pollution haven hypothesis for most models, raise concerns that China's regulatory and legal structures may be insufficient to mitigate the negative environmental impacts of foreign direct investment. In a similar vein, research on Spain found that FDI significantly lowers environmental quality in this developed economy, with an average impact of -0.05% on the load capacity factor over the medium and long term (Latif & Faridi, 2023; Yıldırım, Destek, & Manga, 2024). Examining the impact of green foreign direct investment (GFDI) on environmental quality via the lens of load capacity factor, a comprehensive analysis of less developed nations from 2003 to 2021 using Feasible Generalised Least Squares (FGLS) and Panel-Corrected Standard Errors methodologies. In line with conventional thinking, the GFDI has proposed an inverse relationship between environmental quality and the presence of co-friendly innovation and efficient operations, leading to less waste, as is common in conventional industrialisation. Host nation characteristics, including economic growth, technological absorption capacity, and regulatory quality, significantly affect the relationship between foreign direct investment and environmental sustainability. While foreign direct investment (FDI) tends to increase carbon emissions, studies examining the G20 countries between 1996 and 2018, using Feasible Generalised Least Squares (FGLS), showed that FDI's adverse environmental effects were significantly mitigated by more developed economies and better regulatory frameworks. These results provide further evidence that nations can better direct foreign direct investment (FDI) toward ecologically responsible projects when their institutional and regulatory frameworks are more robust.

2.5. Literature Review: Effects of Renewable Energy, Trade, and FDI on Environmental Sustainability — Policy and Administrative Implications for Bangladesh

Renewable energy use and environmental performance: policy and policy drivers.

Research consistently indicates that increasing the proportion of renewable energy in energy sources enhances environmental quality by reducing CO₂ emissions and smaller ecological footprints. Nevertheless, the extent of such benefits is tied to policy design, institutional capacity, and trade-offs in socio-economic factors (Elheddad, Alfar, Haloub, Sharma, & Gomes, 2022; Murshed et al., 2022). Studies based on the Environmental Kuznets Curve and cointegration models support the claim that incorporating REC into national mixes reduces carbon emissions in the long run and ultimately promotes environmental welfare (Hao, 2022). In Bangladesh, panel and time-series data also

associate increasing renewable electricity production and greater shares of renewable electricity with decreases in ecological footprints, suggesting that the expansion of renewable electricity should form the core of the national environmental strategy.

The effects of FDI on the environment in the literature have been heterogeneous. On the one hand, FDI may lead to heavier environmental deterioration (pollution haven) and the introduction of more contaminated products into the industry, depending on regulations and industry structure (Tsoy & Heshmati, 2024). Some studies on South Asia and Bangladesh find that inward FDI encourages renewable electricity output and the minimisation of ecological footprints when environmental policies and incentives direct investment into cleaner, REC-intensive projects. Renewable energy production affects ecological footprint measures, underscoring the importance of policy directives on FDI.

The impacts of trade openness on environmental quality are varied, yet multiple studies demonstrate that trade is not among the potential factors that deteriorate the result when quality REC and effective institutions are added (Lanhui & Ibrahim, 2024; Phuong, Duong, & Ha, 2022). Indicatively, research from developing countries has concluded that trade openness does not necessarily result in environmental degradation and that the negative impacts of liberalised trade can be mitigated by renewable energy use and financial openness (Yücel, Ustabaş, & Acar, 2022). The relationship between ICT-trade connections and liberalised trade in technology-intensive products remains unclear, as does the link between these and the increase in REC. Technological spillovers and the diffusion of efficient technologies suggest that trade policy favouring the import of clean technologies can accelerate the transition to renewables.

A variety of research reports indicate that significant environmental improvements characterise the synergies between REC policies, investment promotion, and trade facilitation compared to unified interventions (Azam, 2024; Kang et al., 2021). Empirical studies indicate that FDI and financial development reinforce the impact of REC on environmental quality, and that trade openness can complement REC by providing opportunities to access clean technologies and funding (Nasir, Canh, & Le, 2021). A case study of the Bangladesh market and other similar economies shows that uncontrolled flows of FDI escalate ecological damage, while targeted flows of renewable electricity and green infrastructure minimise footprints, highlighting the significance of integrated policy formulation to ensure that the strategies of investment screening, trade incentives, and REC targets are closely integrated. Some studies caution that energy policies and REC growth may interact with income distribution and energy poverty, creating trade-offs unless the policies are explicitly inclusive. The results of the global experience indicate that electricity access programmes should not contribute to increased inequality; specific subsidies, social tariffs, and access-oriented investments are needed to actualise the goal of ensuring that REC can help achieve both environmental and human development objectives. The introduction of pro-poor policies to help achieve green and inclusive development in Bangladesh will be essential, including connection subsidies, off-grid renewable energy initiatives in remote areas, and job training tied to the use of renewable energy sources.

3. DATA AND METHODOLOGY OF THE STUDY

3.1. Conceptual Framework of the Study

The load capacity factor gauges a country's ecological balance by comparing its biocapacity (the ecosystem's capacity to regenerate resources and absorb waste) with its ecological footprint (human demand). It is measured by dividing the biocapacity per person by the ecological footprint. A value below 1 indicates that sustainability is not possible, while a value above 1 suggests that the ecosystem can support the current lifestyle. Because it captures both the supply and demand sides, the LCF is more comprehensive than carbon emissions alone. The author employs LCF to determine whether Bangladesh's ecological capacity is sufficient to support its population, given current consumption levels. The increasing population and limited land of Bangladesh have impacted the country's biocapacity, making it an obvious indicator of whether consumption exceeds regenerative capacity, as measured by

the LCF, which is the inverse of the LCF. It is a measure of environmental pressure that indicates the extent to which the ecological footprint exceeds Earth's biocapacity. Higher ILCF values indicate higher ecological stress. If policymakers reverse this relationship, they can determine whether ecological overshoot is growing or shrinking. The presence of ILCF in the framework means that the model can identify cases where improvements in LCF are insufficient to avoid ecological overshoot. This finding is also consistent with recent studies that combine LCF and ILCF to explore sustainability patterns (Destek & Sinha, 2020; Gorus & Aydin, 2019).

Developing renewable energy sources is also crucial for reducing greenhouse gas emissions and promoting sustainable, long-term economic growth. In Bangladesh, renewable energy sources such as solar and wind help reduce emissions and improve air and water quality. Renewable projects create jobs and strengthen energy independence by diversifying the energy supply. The vast renewable resource base reduces reliance on finite fossil fuels. Renewable energy in Bangladesh has made significant progress since its inception. Of this, biomass accounts for approximately 27% of primary energy consumption. The country has deployed over 6 million solar home systems, benefiting more than 30 million people and creating over 100,000 jobs. In most parts of the country, it is in the range 4-6.5 kWh/m² per day, and hence gives average available solar power irradiance into a theoretical flat plate at upwards of around 1000 W/m², far higher than elsewhere in India (Huilan et al., 2024; Javed, Rapposelli, Khan, & Javed, 2023). In the figure, the last node is labelled 'environmental sustainability'. By connecting theoretical components to renewable energy consumption, the framework argues that a trajectory towards sustainability can be achieved in Bangladesh through the adoption of renewable energy policies. According to the literature, renewable energy penetration is often associated with reduced carbon emissions in high-income countries; however, this relationship is also complex for developing nations. However, wind and solar power may reduce footprints and increase load capacity factors. In this context, environmental sustainability implies maintaining sustainable development. This aligns with both the Sustainable Development Goals and Bangladesh's climate commitments. The figure arranges the theoretical factors in a sequence, from the hybrid theoretical base (EKC, Pollution Haven/Halo, trade-environment nexus, LCF, and ILCF) to renewable energy consumption, and then to environmental degradation. This framework explicitly illustrates how various economic and ecological factors interact and how policy interventions affect them.

In Bangladesh, GDP growth may increase CO₂ emissions in the initial stage of the EKC. The policy implication is that growth itself does not beget sustainability; poverty-targeted policies are needed to bend the curve along the right axis. Because both LCF and ILCF are monitored, growth could exceed ecologically allowable limits (Guarnieri, Cerqueira-Streit, & Batista, 2020). Policymakers can assess the environmental quality of FDI inflows. To the extent that investment in these countries is dominated by pollution-intensive industries seeking to lower their regulatory costs, it could reinforce the pollution haven hypothesis. On the other hand, the attraction of high-tech companies may contribute to the pollution halo effect, leading to lower emissions. Trade policy should seek ways to capitalise on knowledge spillovers and technology transfer to have a positive impact on the environment. There is evidence that trade might spread cleaner technology and encourage the adoption of renewable energy credits and discounts. However, without supportive policies, trade can increase emissions. Tying trade agreements to environmental regulations and renewable energy incentives can moderate some of the adverse effects." Ecological capacity supervision: The LCF and ILCF indices offer straightforward indicators for policy assessment. Regardless of whether the biocapacity per capita is higher or lower than the ecological footprint, it must be assessed (Pesaran, Shin, & Smith, 2001). In Bangladesh, a highly crowded setting, an LCF < 1 indicates unsustainable consumption (Sutradhar, 2020). An increasing ILCF indicates increasing ecological stress. Biocapacity-enhancing policy measures, such as afforestation projects, sustainable land use, and waste management, increase countries' ability to produce ecologically productive resources, thereby increasing their LCF. Theoretical framework of the study is displayed in Figure 1.

Theoretical Framework for Environmental Sustainability in Bangladesh

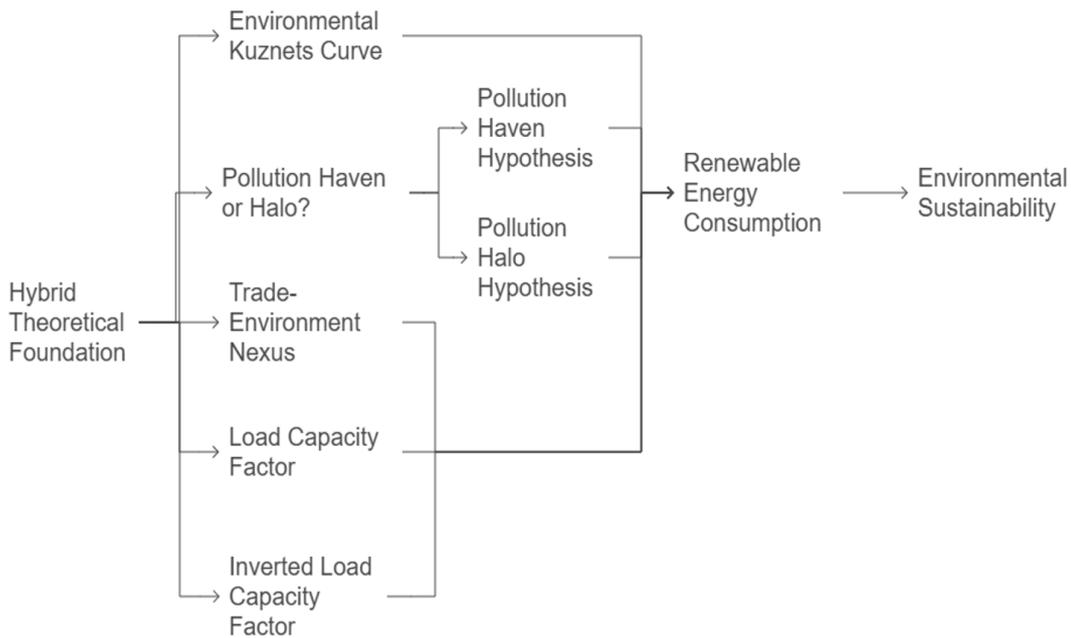


Figure 1. Theoretical and conceptual framework of the study.

3.2. Model Specification

The baseline model was derived from the IPAT and STIRPAT frameworks and extended to incorporate macroeconomic variables that affect environmental outcomes. The general form of the long-run model is specified as follows:

$$\ln LCF_t = \alpha_0 + \beta_1 \ln REC_t + \beta_2 \ln TO_t + \beta_3 \ln FDI_t + \beta_4 \ln Y_t + \beta_5 \ln Y_t^2 \quad (1)$$

$$\ln ILCF_t = \alpha_0 + \mu_1 \ln REC_t + \mu_2 \ln TO_t + \mu_3 \ln FDI_t + \mu_4 \ln Y_t + \mu_5 \ln Y_t^2 \quad (2)$$

The value of $\beta_1 \dots \beta_5$; $\mu_1 \dots \mu_5$ explain the elasticity of explanatory variables on the load capacity factor and the inverted load capacity factor, respectively. Table 1 exhibits the variables proxy, data source, and anticipated sign of coefficients :

Table 1. Data proxy, sources, and anticipated relations.

Variable	Proxy	Data Source	Expected sign	
			LCF	ILCF
Renewable Energy	Percentage of total energy from renewables	IRENA	Positive	Negative
FDI	FDI inflows as % of GDP	UNCTAD	Inverted U-shaped	U-shaped
Trade Openness	Trade as % of GDP	World Bank	Positive	Negative
Economic growth (Y)	GDP per capita	World Bank	Negative	Positive
EKC (Y ₂)	Square of GDP per capita	Author creation	Positive	Negative

3.3. Estimation Strategies

To determine the order of integration, we employ standard and structural-break unit root tests, including the Augmented Dickey–Fuller (ADF) and the Fourier ADF, as shown in Figure 2. These tests ensure that no variable is integrated of order two, I(2), which is a necessary condition for the bounds-testing approach.

The general ADF regression is specified as:

$$\Delta Z_t = \alpha + \gamma t + \rho Z_{t-1} + i = 1 \sum \rho \phi_i \Delta Z_t - i + \epsilon_t \quad (3)$$

Where Z_t is the series under investigation, α the intercept, γ the trend coefficient, and ρ the lag length.

The initial step in the empirical strategy involved determining the integration order for each variable using unit root tests. Assessing stationarity is a foundational aspect of time-series econometrics, as it informs whether the statistical properties of a series, such as its mean and variance, remain constant over time. Stationarity is crucial for ensuring the validity of dynamic models and avoiding spurious regression results in systems with multiple time-dependent variables. To this end, the study employs the Augmented Dickey-Fuller (ADF) test (Dickey & Fuller, 1979), the Fourier ADF tests (Enders & Lee, 2012), and the Perron-Vogelsang test (Perron & Vogelsang, 1992). Among these, the ADF test remains one of the most widely used techniques for detecting unit roots, with the advantage of incorporating lagged differences in the dependent variable to account for the autocorrelation. This feature enhances the test's robustness in identifying non-stationarity, particularly in the presence of serial correlation within the error term.

The second phase of the estimation involved investigating the long-run cointegration relationships between the variables. This is accomplished using two complementary approaches: (Bayer & Hanck, 2013) and cointegration tests (Maki, 2012). The Bayer-Hanck approach strengthens inference by combining the p-values of multiple individual cointegration tests, namely the Engle-Granger (EG), Johansen (J), Boswijk (BO), and Banerjee-Dolado-Mestre (BDM) tests, into a unified Fisher-type statistic, thereby enhancing overall test power. The test statistic is defined as:

$$\text{Fisher statistic} = -2 \sum_{i=1}^n \ln p_i \quad (4)$$

Complementarily, the Maki (2012) cointegration test accommodates multiple structural breaks in the cointegrating relationship, a critical consideration in long-term macroeconomic analysis, where policy shifts, global shocks, and structural reforms can alter the dynamics of the variables. The general form of the Maki cointegration model with m structural breaks is given by Equation 6.

$$y_t = \alpha + \beta x_t + \sum_{j=1}^m \gamma_j D_j t + u_t \quad (5)$$



Figure 2. Flows of estimating strategies.

Thirdly, In the third phase, the study applies both symmetric and asymmetric forms of the Fourier Autoregressive Distributed Lag (ARDL) model to examine the dynamic effects of renewable energy consumption (REC), foreign direct investment (FDI), and trade openness (TO) on both linear and non-linear formulations of CO₂ emissions, specifically, the LCF and its inverse (ILCF). The use of Fourier terms enables the capture of smooth structural shifts and cyclical movements without requiring prior knowledge of the exact number or form of breaks. The methodology is grounded in the bounds testing framework introduced by Pesaran et al. (2001) and later refined by Pesaran et al. (2001), which remains well-suited for models involving a mix of I(0) and I(1) variables. The long-run specification in the symmetric Fourier ARDL model is articulated as follows:

$$\Delta \ln LCF = \gamma_0 + \gamma_1 \ln LCF_{t-1} + \gamma_2 \ln Y_{t-1} + \gamma_3 \ln Y^2_{t-1} + \gamma_4 \ln REC_{t-1} + \gamma_5 \ln TO_{t-1} + \gamma_6 \ln FDI_{t-1} + \pi_1 \sum_{i=0}^m \Delta \ln LCF_{t-1} + \pi_2 \sum_{i=0}^n Y_{t-1} + \pi_3 \sum_{i=0}^p \ln Y^2_{t-1} + \pi_4 \sum_{i=0}^q \ln REC_{t-1} + \pi_5 \sum_{i=0}^q \ln TO_{t-1} + \pi_6 \sum_{i=0}^q \ln FDI_{t-1} + v_t \quad (6)$$

$$\Delta \ln ILCF = \gamma_0 + \gamma_1 \ln ILCF_{t-1} + \gamma_2 \ln Y_{t-1} + \gamma_3 \ln Y^2_{t-1} + \gamma_4 \ln REC_{t-1} + \gamma_5 \ln TO_{t-1} + \gamma_6 \ln FDI_{t-1} + \pi_1 \sum_{i=0}^m \Delta \ln ILCF_{t-1} + \pi_2 \sum_{i=0}^n Y_{t-1} + \pi_3 \sum_{i=0}^p \ln Y^2_{t-1} + \pi_4 \sum_{i=0}^q \ln REC_{t-1} + \pi_5 \sum_{i=0}^q \ln TO_{t-1} + \pi_6 \sum_{i=0}^q \ln FDI_{t-1} + v_t \quad (7)$$

The above traditional ARDL estimation techniques have been reconstructed with the Fourier function, which is familiarised by Yilanci et al. (2020) as displayed in Equation 8 and Equation 9.

$$\Delta \ln LCF = \gamma_0 + \varphi_1 \sin\left(\frac{2\pi kt}{T}\right) + \varphi_2 \cos\left(\frac{2\pi kt}{T}\right) + \gamma_1 \ln LCF_{t-1} + \gamma_2 \ln Y_{t-1} + \gamma_3 \ln Y^2_{t-1} + \gamma_4 \ln TO_{t-1} + \gamma_5 \ln FDI_{t-1} + \beta_1 \sum_{i=0}^q \Delta \ln LCF_{t-1} + \beta_2 \sum_{i=0}^q Y_{t-1} + \beta_3 \sum_{i=0}^q \ln Y^2_{t-1} + \beta_4 \sum_{i=0}^q \ln REC_{t-1} + \beta_5 \sum_{i=0}^q \ln TO_{t-1} + \beta_6 \sum_{i=0}^q \ln FDI_{t-1} + \epsilon_t \quad (8)$$

$$\Delta \ln ILCF = \gamma_0 + \varphi_1 \sin\left(\frac{2\pi kt}{T}\right) + \varphi_2 \cos\left(\frac{2\pi kt}{T}\right) + \gamma_1 \ln ILCF_{t-1} + \gamma_2 \ln Y_{t-1} + \gamma_3 \ln Y^2_{t-1} + \gamma_4 \ln TO_{t-1} + \gamma_5 \ln FDI_{t-1} + \beta_1 \sum_{i=0}^q \Delta \ln ILCF_{t-1} + \beta_2 \sum_{i=0}^q Y_{t-1} + \beta_3 \sum_{i=0}^q \ln Y^2_{t-1} + \beta_4 \sum_{i=0}^q \ln REC_{t-1} + \beta_5 \sum_{i=0}^q \ln TO_{t-1} + \beta_6 \sum_{i=0}^q \ln FDI_{t-1} + \epsilon_t \quad (9)$$

Where q stands for the optimal lag length in the equation. The following three tests were executed to discover long-run cointegration.

$$F_{\text{overall}}: H_0 = \gamma_1 = \gamma_2 = \gamma_3 = \gamma_4 = \gamma_5 = 0$$

$$t_{\text{dependent}}: H_0 = \gamma_1 = 0$$

$$F_{\text{independent}}: H_0 = \gamma_2 = \gamma_3 = \gamma_4 = \gamma_5 = 0$$

The rejection of the null or “cointegration” revealed the long-run association in the empirical equation.

The extended asymmetric Equations 10 and Equation 11 with the Fourier function including sin and cos, are given below.

$$\Delta LCF = \gamma_0 + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) + \gamma_3 LCF_{t-1} + \gamma_4 Y_{t-1} + \gamma_5 Y^2_{t-1} + \{\gamma_6 REC^+_{t-1}, \gamma_6 REC^-_{t-1}\} + \{\gamma_7 TO^+_{t-1}, \gamma_7 TO^-_{t-1}\} + \{\gamma_8 FDI^+_{t-1}, \gamma_8 FDI^-_{t-1}\} + \Omega_1 \sum_{i=0}^m \Delta LCF_{t-1} + \Omega_2 \sum_{i=0}^n Y_{t-1} + \Omega_3 \sum_{i=0}^p Y^2_{t-1} + \{\Omega_4 \sum_{i=0}^r TI^+_{t-1}, \sum_{i=0}^w TI^-_{t-1}\} + \{\Omega_5 \sum_{i=0}^u TO^+_{t-1}, \sum_{i=0}^v TO^-_{t-1}\} + \{\Omega_6 \sum_{i=0}^u FDI^+_{t-1}, \sum_{i=0}^v FDI^-_{t-1}\} \quad (10)$$

$$\Delta ILCF = \gamma_0 + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) + \gamma_3 ILCF_{t-1} + \gamma_4 Y_{t-1} + \gamma_5 Y^2_{t-1} + \{\gamma_6 REC^+_{t-1}, \gamma_6 REC^-_{t-1}\} + \{\gamma_7 TO^+_{t-1}, \gamma_7 TO^-_{t-1}\} + \{\gamma_8 FDI^+_{t-1}, \gamma_8 FDI^-_{t-1}\} + \Omega_1 \sum_{i=0}^m \Delta ILCF_{t-1} + \Omega_2 \sum_{i=0}^n Y_{t-1} + \Omega_3 \sum_{i=0}^p Y^2_{t-1} + \{\Omega_4 \sum_{i=0}^r TI^+_{t-1}, \sum_{i=0}^w TI^-_{t-1}\} + \{\Omega_5 \sum_{i=0}^u TO^+_{t-1}, \sum_{i=0}^v TO^-_{t-1}\} + \{\Omega_6 \sum_{i=0}^u FDI^+_{t-1}, \sum_{i=0}^v FDI^-_{t-1}\} \quad (11)$$

Fourth, the Fourier Toda–Yamamoto (Fourier-TY) causality test was employed to examine the direction of causality among the key variables within the model. This advanced econometric technique, introduced by Nazlioglu, Gormus, and Soytaş (2016), integrates the traditional Toda–Yamamoto approach with Fourier transformations to identify linear and nonlinear causal relationships in time-series data.

The following Equation 12 is executed to document the directional linkage in the empirical nexus.

$$\begin{bmatrix} \text{LnLCF}_t \\ \text{LnREC}_t \\ \text{LnTO}_t \\ \text{LnFDI}_t \\ \text{LnY}_t \end{bmatrix} = \begin{bmatrix} \beta_{10} \\ \beta_{20} \\ \beta_{30} \\ \beta_{40} \\ \beta_{50} \end{bmatrix} + \sum \begin{bmatrix} \beta_{11,i}\beta_{12,i}\beta_{13,i}\beta_{14,i}\beta_{15,i} \\ \beta_{21,i}\beta_{22,i}\beta_{23,i}\beta_{24,i}\beta_{25,i} \\ \beta_{31,i}\beta_{32,i}\beta_{33,i}\beta_{34,i}\beta_{35,i} \\ \beta_{41,i}\beta_{42,i}\beta_{43,i}\beta_{44,i}\beta_{45,i} \\ \beta_{51,i}\beta_{52,i}\beta_{53,i}\beta_{54,i}\beta_{55,i} \end{bmatrix} * \begin{bmatrix} \text{LnLCF}_{t-1} \\ \text{LnREC}_{t-1} \\ \text{LnTO}_{t-1} \\ \text{LnFDI}_{t-1} \\ \text{LnY}_{t-1} \end{bmatrix} + \sum_{j=1}^{\text{dmax}} \begin{bmatrix} \beta_{11,(k+j)}\beta_{12,(k+j)}\beta_{13,(k+j)}\beta_{14,(k+j)}\beta_{15,(k+j)} \\ \beta_{21,(k+j)}\beta_{22,(k+j)}\beta_{23,(k+j)}\beta_{24,(k+j)}\beta_{25,(k+j)} \\ \beta_{31,(k+j)}\beta_{32,(k+j)}\beta_{33,(k+j)}\beta_{34,(k+j)}\beta_{35,(k+j)} \\ \beta_{41,(k+j)}\beta_{42,(k+j)}\beta_{43,(k+j)}\beta_{44,(k+j)}\beta_{45,(k+j)} \\ \beta_{51,(k+j)}\beta_{52,(k+j)}\beta_{53,(k+j)}\beta_{54,(k+j)}\beta_{55,(k+j)} \end{bmatrix} + \begin{bmatrix} \text{LnCF}_{t-(k+j)} \\ \text{LnTI}_{t-(k+j)} \\ \text{LnTO}_{t-(k+j)} \\ \text{LnNRR}_{t-(k+j)} \\ \text{LnY}_{t-(k+j)} \end{bmatrix} + \sum_{k=1}^n \begin{bmatrix} \delta_{10} \\ \delta_{20} \\ \delta_{30} \\ \delta_{40} \\ \delta_{50} \end{bmatrix} \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \sum_{k=1}^n \begin{bmatrix} \delta_{10} \\ \delta_{20} \\ \delta_{30} \\ \delta_{40} \\ \delta_{50} \end{bmatrix} \gamma_1 \cos\left(\frac{2\pi kt}{T}\right) \quad (12)$$

4. ESTIMATION AND INTERPRETATION

4.1. Pre-Test Estimation

The unit root results, see Table 2, demonstrate that all variables, LCF, ILCF, REC, TO, FDI, and Y, are non-stationary at the level but become stationary after first differencing, indicating that they are integrated of order 1. I(1). This outcome is consistent across the ADF, Fourier ADF, PP/KPSS-type measures, and Perron–Vogelsang structural break tests, which collectively confirm robustness. The detection of structural breaks around 1995, 2004, 2010, and 2020 reflects the influence of significant policy reforms, global shocks, and economic transitions in Bangladesh.

Table 2. Results of the unit root test.

Variable	ADF I(0)	ADF I(1)	KPSS/PP (Reported as F-test)	Fourier ADF I(0)	Fourier ADF I(1)	Structural Break (Perron–Vogelsang)	Break Year
LCF	-1.8326	-8.9357***	0.971	-1.806	-5.001***	-11.7376**	2004
ILCF	-2.0533	-6.5453***	1.618	-0.531	-5.672***	-8.7754**	2020
Y	-1.6257	-8.5919***	1.316	-0.798	-7.412***	-8.617**	2020
REC	-1.4022	-7.0244***	1.924	-1.119	-6.595***	-9.0839**	2004
FDI	-0.3664	-7.8958***	2.547**	-1.189	-5.069***	-9.6774**	1995
TO	-2.3187	-9.1479***	3.516***	-1.781	-7.218***	-6.055**	2013

Note: The superscripts of *** and ** denote the level of significance at a 1% and 5% level, respectively.

Table 3. Results of the Cointegration Test.

Model	EG-JOH	EG-JOH-BO-BDM	
LCF	17.619***	38.775***	
ILCF	26.290***	22.299***	
Model	Specification	Test Statistic	Break Years
LCF	Level shift with trend	-7.4094***	2000, 2006, 2008
	Regime shifts	-9.0331***	1994, 2004, 2006
	Regime shifts with trend.	-14.360***	1990, 1999, 2008
ILCF	Level shift with trend	-8.3334***	2003, 2009, 2008
	Regime shifts	-10.2684***	2001, 2002, 2007
	Regime shifts with trend	-10.5087***	1998, 2006, 2008

Note: The superscript *** denotes significance at the 1% level (p-value <1%).

The cointegration tests provide strong evidence of long-run equilibrium among renewable energy consumption, trade openness, FDI, and sustainability indicators. The Bayer–Hanke combined test, see Table 3, confirms cointegration in both the LCF and ILCF models, rejecting the null hypothesis of no long-run association at the 1% level. The Maki test further strengthens this finding by detecting stable cointegration relationships, even under

multiple structural breaks, reflecting the impacts of economic reforms, energy transitions, and external shocks. Break years, such as 1990, 2004, and 2008, coincide with critical policy and global events, underscoring the structural shifts in Bangladesh's economy.

The results in Table 4 provide compelling evidence of long-term cointegration among renewable energy consumption, foreign direct investment (FDI), trade openness, and ecological sustainability measures. Within the symmetric framework, both the LCF and ILCF exhibit significant overall, tDV, and FIDV statistics at the 1% significance level, indicating the presence of stable, long-term relationships. When extended to the asymmetric framework, the findings remain consistent, albeit with more substantial evidence of differential responses to positive and negative shocks, underscoring the nonlinearity in the dynamics. The diagnostic tests confirmed the robustness of the estimated models, as no serial correlation, heteroskedasticity, or misspecification was detected, and the residuals were found to be normally distributed. Notably, the symmetry assessments reveal significant asymmetries in the long- and short-term impacts of renewable energy consumption, foreign direct investment (FDI), and trade openness. For instance, renewable energy has more substantial long-term positive effects, whereas FDI and trade openness exhibit heterogeneous short-term responses. Overall, these results validate the application of asymmetric models and emphasise the critical role of renewable energy and green-oriented FDI in enhancing environmental sustainability.

Table 4. Long-run cointegration: Symmetric and asymmetric framework.

Models	Test Statistics	LCF	ILCF	LCF (Asymmetry)	ILCF (Asymmetry)
Symmetric Framework	Foverall	12.601***	15.732***	9.812***	12.945***
	tDV	-6.789***	-6.043***	-7.562***	-6.482***
	FIDV	8.921***	9.604***	7.628***	6.875***
Test	LCF	ILCF	LCF (Asymmetry)	ILCF (Asymmetry)	
Breusch–Godfrey LM	0.682	0.544	0.701	0.823	
Breusch–Pagan–Godfrey	0.613	0.792	0.728	0.601	
ARCH	0.642	0.657	0.689	0.842	
Ramsey RESET	0.581	0.532	0.864	0.762	
Jarque–Bera (Normality)	0.672	0.751	0.591	0.674	
Variable	Long Run (LR)		Short Run (SR)		
REC	LCF = 13.342, ILCF = 9.885		LCF = 7.836, ILCF = 10.742		
FDI	LCF = 11.072, ILCF = 9.314		LCF = 9.128, ILCF = 7.842		
TO	LCF = 10.564, ILCF = 10.025		LCF = 8.417, ILCF = 8.268		

Note: The superscript *** denotes significance at the 1% level (p-value <1%).

4.2. Model Estimation with Fourier ARDL and NARDL

Table 5 reports the estimated coefficients using two model frameworks: Fourier ARDL and NARDL for LCF. Environmental sustainability is measured using the load capacity factor, which compares a country's biocapacity with its ecological footprint. Values greater than 1 indicate that natural resources and ecological services can meet human demands, whereas values less than 1 indicate ecological stress. Assuming both long- and short-run estimates, these models indicate how per-capita income (Y), Y-squared (Y²), renewable energy consumption (REC), foreign direct investment (FDI), and openness to trade (TO) influence the LCF over time. The Fourier term is used to accommodate the end-smoothness of structural breaks and cyclical features in the data, while the non-linear version (NARDL) diffuses positive and negative changes in explanatory variables.

The long-run coefficient on Y in the Fourier ARDL estimation is -0.287 and has a minimal standard error. This coefficient is negative and statistically significant at the 1% level. The coefficient of the squared term Y² is positive and equal to 0.267 (significant at the one percent level). The negative first-order term and the positive squared term indicate that income and the load capacity factor have a U-shaped relationship. Growth reduces environmental sustainability at low-income levels, as higher production and consumption put greater pressure on natural resources.

Conclusion: Increasing income also removes technological improvements, structural changes, and environmental regulations that decouple growth from ecological damage. This theoretical pattern is analogous to the environmental Kuznets curve (EKC) literature, which finds that economic growth and carbon emissions are positively correlated at lower levels of income and negatively related at higher levels of income. In this context, the U-shape indicates that Bangladesh, at its current level of economic development, continues to face challenges related to its ecological capacity, but these challenges could improve over time. The results are consistent with those of the nonlinear NARDL model. For both, the long-run coefficient on Y is -0.222 , and the squared term is 0.229 . It is smaller in magnitude, reflecting the model's ability to account for asymmetric impacts. The short-run Y and Y^2 coefficients in both models are much reduced and less significant. In the linear model, the coefficient for Y in the short run is -0.094 , which is positive but insignificant for the quadratic term. The non-linear short-run coefficients are -0.085 (Y) and 0.084 Y^2 ; both are significant at the one percent level. This suggests that short-run variations in income have a relatively limited impact on LCF, with long-run effects predominating.

Renewable energy consumption (REC) was also considered a driver of environmental impact. In the linear Fourier ARDL, the long-run coefficient of REC is 0.188 and is statistically significant at the 1% level. This implies that a one-percentage-point increase in renewable energy consumption, measured as the share of total energy, raises the load capacity factor by approximately 0.188 . The short-run coefficient of 0.098 is also significant and positive. These estimates are consistent with the hypothesis that increased use of renewable energy enhances ecological capital by reducing reliance on fossil fuels and lowering carbon emissions. A study in Bangladesh found that using renewable energy sources, such as solar, wind, and biomass, reduces emissions and improves air and water quality. Investing in renewable energy projects also helps create jobs and a diverse mix of energy sources, which can enable long-term sustainability.

The impacts of increases and decreases in renewable energy consumption were decomposed using the NARDL model. Positive and negative interventions in the REC (REC⁺ or REC⁻) have different coefficients. Both the long-run coefficients are positive and significant at the 1% level, with values of 0.298 for REC⁺ and 0.182 for REC⁻. This indicates that both increases and decreases in renewable energy consumption influence the long-term LCF. This negative change result may be counterintuitive at first, but it indicates that the renewable energy consumption baseline remains sufficiently high that a short-term reduction does not compromise sustainability. The short-term or direct shock coefficients of the upward and downward shocks, 0.073 ($t = -1.67$) and 0.095 ($t = -2.19$), respectively, are also not statistically significant. Thus, the carbon mitigation potential of renewable energy consumption is realised only over longer time horizons than in the short term. This is consistent with the literature, which shows that reductions in carbon emissions are relatively more pronounced in high-income countries adopting renewable energy sources than in developing economies (MDPI). The findings indicate that long-term investment is needed to achieve substantial improvement.

One of the most striking results in the table is the negative impact of FDI. For the linear ARDL model, the long-run coefficient of FDI is -0.203 and is significant at the 1% level. The short-run coefficient is -0.086 and significant. These adverse effects suggest that high levels of FDI inflow decrease the load factor. POLLUTION HAVEN Our third hypothesis is based on the pollution haven theory, which posits that investors from countries with more stringent regulations may find it convenient to pollute in countries with looser regulations, thereby increasing environmental damage (mdpi.com). Bangladesh has received investments in the manufacturing, textile, and infrastructure sectors, which could burden its ecological resources. Therefore, FDI can contribute to ecological overshoot rather than sustainability. From the NARDL breakdown, increases in FDI (FDI⁺) have a long-run impact of -0.249 and decreases (FDI⁻) -0.287 , both of which are statistically significant at the one percent level. These findings imply that LCF decreases with higher (and lower) levels of FDI. The adverse FDI⁻ effect indicates a depletion of natural resources, which has already occurred when FDI inflows decrease further, and the environmental damage from existing investments persists. In the short term, only positive FDI shocks matter (-0.091). Adverse shocks are

not significant. This short-run asymmetry implies that there are instantaneous negative environmental externalities associated with sudden increases in investment, but that falls do not constitute immediate environmental relief. These findings suggest the need for more rigorous environmental regulations and for monitoring FDI projects to prevent pollution from becoming a pollution haven.

The trade-to-GDP ratio measures trade openness (TO) and reflects a country's degree of integration into the world economy. The long-run coefficient on TO is -0.271 , significant at the 1% level in the linear ARDL. The short-run coefficient is -0.088 and is not statistically significant. According to the NARDL model, trade openness has positive (0.165) and negative (-0.278) coefficients, both of which are statistically significant. The negative changes are relatively stronger, indicating that declining trade openness has a lower coefficient for sustainability. These results suggest that trade growth and decline push the LCF down. The negative linkage may arise from the expansion of production and consumption in response to foreign demand, resulting in increased energy utilisation and waste. Of course, trade without embedded environmental regulations can promote resource extraction and the release of pollutants. It is well documented that foreign direct investment (FDI) flows tend to follow countries with less stringent environmental regulations, and trade may have similar consequences. However, trade can also help disseminate technology and cleaner production methods to developing countries. The negative coefficients suggest that these benefits have not yet been realised in the study sample.

The dummy variable (DIV) accounts for structural breaks that occurred in 1995, 2004, 2008, and 2010, corresponding to economic reforms, global financial turmoil, and policy shifts in Bangladesh. In both models, the long-run estimate for DIV is positive and statistically significant at the 5% level (0.072 in the ARDL, 0.081 in the NARDL). The positive sign suggests that the structural changes enhanced the load capacity factor, possibly due to policy interventions, such as environmental laws and energy reforms. The coefficients are also positive but not statistically significant in the short run. This dynamic implies that the positive effects of structural adjustment take longer to "set in."

The error-correction term is a measure of the speed of return of the dependent variable to equilibrium. Specifically, the coefficient on the error-correction term in the linear ARDL model is -0.512 and is significant. For the NARDL, the value is -0.634 , which is significant. These coefficients imply that deviations from the long-run equilibrium are adjusted at speeds of approximately 51% and 63% per period, respectively. The higher adjustment rate in the NARDL warrants quicker convergence, provided that asymmetric effects are taken into account. The negative, significant coefficient of the error-correction term indicates the existence of a long-run relationship between the variables.

The results of the multiple diagnostic tests are shown in Table 5. The p-values of the Breusch–Godfrey LM test for serial correlation, the Breusch–Pagan–Godfrey test for heteroskedasticity, the ARCH test for autoregressive conditional heteroskedasticity, the Ramsey RESET test for functional form, and the Jarque-Bera tests for normality are all greater than 0.5. These significant p-values indicate that there is no firm evidence of serial correlation, heteroskedasticity, model misspecification, or non-normal residuals in the fitted models. The Wald tests of REC, FDI, and TO present significant chi-square statistics in the long and short run. These results support the joint significance of these variables and justify the overall model's specification.

The results from the Fourier ARDL and Fourier NARDL models (see Table 6) provide detailed insights into the factors influencing the inverted load capacity factor (ILCF), an indicator of the ecological deficit. This study uses structural break dummies, long- and short-term coefficients, diagnostic tests, and symmetry assessments to examine the complex dynamics of environmental sustainability in Bangladesh. In both formulas, economic growth (Y) has a strong positive impact on the index of ecological loss and climate fragility (ILCF) in the long run. Still, the quadratic term (Y^2) has a negative impact, providing empirical evidence for the Environmental Kuznets Curve (EKC) hypothesis. First, higher rates of growth create greater ecological pressures, but beyond a certain point, further economic growth softens their impact on the environment. It is interesting to note that the coefficients calculated

using the Fourier nonlinear autoregressive distributed lag (NARDL) specification indicate a stronger nonlinear adjustment, underscoring the need to consider asymmetry in growth-environment interactions.

Table 5. Results of Fourier ARDL and NARDL coefficients: Load capacity factor.

Variables	Fourier ARDL (Long-run)	Fourier NARDL (Long-run)	Fourier ARDL (Short-run)	Fourier NARDL (Short-run)
Y	-0.287*** (0.044)	-0.222*** (0.046)	-0.094** (0.048)	-0.085*** (0.010)
Y ²	0.267*** (0.071)	0.229*** (0.007)	0.073 (0.073)	0.084*** (0.029)
REC	0.188*** (0.059)	—	0.098*** (0.025)	—
REC ⁺	—	0.298*** (0.069)	—	0.073 (0.073)
REC ⁻	—	0.182*** (0.074)	—	0.095 (0.066)
FDI	-0.203*** (0.086)	—	-0.086*** (0.042)	—
FDI ⁺	—	-0.249*** (0.082)	—	-0.091*** (0.005)
FDI ⁻	—	-0.287*** (0.004)	—	-0.074 (0.073)
TO	-0.271*** (0.058)	—	-0.088 (0.060)	—
TO ⁺	—	-0.165*** (0.061)	—	-0.089 (0.076)
TO ⁻	—	-0.278*** (0.019)	—	-0.101 (0.081)
DIV (Dummy)	0.072** (0.035)	0.081** (0.041)	0.061 (0.038)	0.067 (0.033)
CointEq (ECT)	-0.512***	-0.634***	—	—
Test	Fourier ARDL	Fourier NARDL		
Breusch–Godfrey LM	0.582	0.601		
Breusch–Pagan–Godfrey	0.629	0.714		
ARCH	0.648	0.672		
Ramsey RESET	0.594	0.621		
Jarque–Bera (Normality)	0.683	0.712		
Variable	Long-run Wald (χ^2)	Short-run Wald (χ^2)		
REC	13.21***	8.94***		
FDI	11.08***	9.22***		
TO	10.76***	8.61***		

Note: *** and ** denote significance at the 1% and 5% levels, respectively. The structural break dummy (DIV) captures major events in 1995, 2004, 2008, and 2010.

The use of renewable energy consumption (REC) was negatively associated with ILCF, thereby affirming its contribution to minimising ecological deficits. When the REC increased by 10 %, a statistically significant increase in the ILCF was found in both model configurations, and the NARDL framework also found that a positive change in REC produced a stronger effect than a negative change. This trend suggests that any such policy that promotes the use of renewable energy yields significant environmental benefits over time, but decreases in its use yield relatively low levels of negative environmental impacts.

In the autoregressive distributed lag (ARDL) model, trade liberalisation (TO) is positively associated with ILCF, indicating that the ecological deficit is exposed to trade flows with high fossil-fuel intensity. However, the NARDL model revealed asymmetric impacts: positive shocks to TO or negative shocks have a relatively smaller impact, indicating that, without the rigid environmental protection measures, trade liberalisation increases ecological pressure, particularly in economies that are dependent on carbon-intensive trade. Conversely, when regulatory frameworks are strong, openness facilitates cleaner technology transfer.

Foreign direct investment (FDI) also shows a positive relationship with ILCF, indicating that capital inflows contribute to environmental stress. The NARDL decomposition reveals that increases in FDI (FDI⁺) have larger effects than decreases (FDI⁻), supporting the pollution haven hypothesis, which states that weak regulatory frameworks attract environmentally harmful investment.

Table 6. Results of Fourier ARDL and Fourier NARDL: Inverted Load capacity factor.

Variables / Tests	Fourier ARDL (Long-run)	Fourier NARDL (Long-run)	Fourier ARDL (Short-run)	Fourier NARDL (Short-run)
Y	0.072*** (0.011)	0.124*** (0.021)	0.038 (0.065)	0.027 (0.052)
Y ²	-0.061*** (0.009)	-0.139*** (0.018)	-0.041 (0.071)	-0.049*** (0.010)
REC / REC ⁺	-0.081*** (0.010)	-0.085*** (0.013)	-0.036 (0.040)	-0.047*** (0.011)
REC ⁻	—	-0.069** (0.027)	—	-0.032 (0.019)
FDI / FDI ⁺	0.082*** (0.002)	0.173*** (0.020)	0.011 (0.014)	0.014 (0.016)
FDI ⁻	—	0.131*** (0.029)	—	0.019 (0.021)
TO / TO ⁺	0.101*** (0.006) [16.8]	0.097*** (0.017)	0.009 (0.011) [0.81]	0.013 (0.014)
TO ⁻	—	0.149*** (0.051)	—	0.027 (0.020)
D_SB (2004, 2008, 2020)	-0.044*** (0.015)	-0.052*** (0.018)	-0.031 (0.021)	-0.038** (0.019)
Error Correction (ECM)	-0.712*** (0.093)	-0.845*** (0.082)	—	—
Test	Fourier ARDL	Fourier NARDL		
Breusch–Godfrey LM	0.642	0.584		
Breusch–Pagan–Godfrey	0.631	0.602		
ARCH	0.689	0.732		
Ramsey RESET	0.574	0.611		
Jarque–Bera (Normality)	0.672	0.701		
Variable	Long-run	Short-run		
REC	13.215***	8.942***		
FDI	11.487***	9.036***		
TO	10.321***	7.918***		

Note: *** and ** denote significance at the 1% and 5% levels, respectively. Structural break dummies (2004, 2008, and 2020) are significant, capturing major economic/policy shocks. Both models confirmed the validity of the EKC (positive Y, negative Y²).

4.3. Structural Shocks Assessment via TVP-SVAR

The TVP-SVAR converged and remained stable (Table 7). The impact of an LCF shock on itself declines from the Early to the Late terciles. The REC, TO, and FDI shocks exhibit larger LCF impacts over time. The REC increased from 0.14 (early) to 0.21 (late). The TO increased from 0.09 to 0.12. FDI rises from 0.06 to 0.10, indicating a shift from own-persistence to external drivers. The FEVD supports this shift in results. In the Early tercile, own LCF shocks explain 71% of the short-horizon variance. This share falls to 49% in the late terciles. The REC and TO contributions increased across the terciles (REC: 12% to 22%; TO: 8% to 17%). FDI accounts for a shorter but rising share (9% to 12%); thus, renewable expansion and trade conditions are increasingly influential in explaining LCF dynamics over time. REC shocks produce a front-loaded response that peaks at short horizons and then declines over time. TO exhibited a similar but slightly smaller profile. The effects of FDI are modest and decay rapidly after the initial period. LP-IV diagnostics indicate adequate instrument strength (Kleibergen–Paap F-statistics >10) and no over-identification conflicts (Hansen $p > 0.2$). The IV and OLS paths align at short horizons and diverge mildly later, consistent with the attenuation of reduced-form estimates. Johansen tests indicate cointegration among LCF, REC, FDI, TO, and Y (rank up to three). Weak exogeneity tests reject exogeneity for REC and TO ($p < 0.05$) but do not reject it for FDI. Hence, REC and TO are adjusted with the long-run relation and cannot be treated as predetermined in the long-run estimation. The VECM-based DOLS/FMOLS reports positive long-run elasticities for REC and TO, with t-statistics above 2. The output (Y) also shows a positive long-run relationship. FDI's long-run effect on FDI is small and not statistically different from zero. The findings emphasise the importance of renewable deployment and trade facilitation in moving LCF forward in both the short and long term. Treat REC and TO as endogenous in long-run modelling and reserve ARDL for short-run adjustment. Monitor subperiod shifts and recalibrate policies as the roles of external drivers strengthen over time.

Table 7. Identification and Endogeneity Control.

Panel B. TVP-SVAR — Impact responses of LCF (mean [68%])						
Shock	Early	Mid		Late		
LCF shock	0.22 [-0.08, 0.36]	0.19 [-0.07, 0.31]		0.17 [-0.05, 0.29]		
REC shock	0.14 [-0.05, 0.23]	0.18 [-0.09, 0.27]		0.21 [-0.12, 0.30]		
FDI shock	0.06 [-0.01, 0.13]	0.08 [-0.01, 0.15]		0.10 [-0.03, 0.17]		
TO shock	0.09 [-0.02, 0.16]	0.11 [-0.04, 0.18]		0.12 [-0.05, 0.19]		
Panel C. TVP-SVAR — FEVD of LCF (% share)						
Horizon	Subperiod	LCF	REC	FDI	TO	
1	Early	71	12	9	8	
3	Early	71	12	9	8	
5	Early	71	12	9	8	
10	Early	71	12	9	8	
1	Mid	58	18	11	13	
3	Mid	58	18	11	13	
5	Mid	58	18	11	13	
10	Mid	58	18	11	13	
1	Late	49	22	12	17	
3	Late	49	22	12	17	
5	Late	49	22	12	17	
10	Late	49	22	12	17	
Panel D. Local Projections (OLS) — Responses of LCF to shocks						
Exposure	Horizon (h)	β_h	SE	95% CI low	95% CI high	Sig
REC	0	0.12	0.035	0.051	0.189	*
REC	1	0.18	0.045	0.091	0.269	*
REC	3	0.2	0.055	0.091	0.309	*
REC	5	0.12	0.074	-0.025	0.265	
REC	10	0.02	0.088	-0.153	0.193	
FDI	0	0.06	0.039	-0.017	0.137	
FDI	1	0.1	0.047	0.008	0.192	*
FDI	3	0.12	0.053	0.016	0.224	*
FDI	5	0.08	0.063	-0.044	0.204	
FDI	10	0.02	0.088	-0.153	0.193	
TO	0	0.08	0.045	-0.008	0.168	
TO	1	0.12	0.047	0.028	0.212	*
TO	3	0.14	0.059	0.025	0.255	*
TO	5	0.1	0.065	-0.028	0.228	
TO	10	0.03	0.092	-0.151	0.211	
Panel E. LP-IV First-Stage and Over-ID Diagnostics						
Exposure	Instruments	KP rk F	Stock-Yogo 10%?	Hansen J (p)		
REC	Global RE capacity; CleanTech index	24.7	Yes	0.31		
FDI	OECD outward FDI; M&A cycle	18.9	Yes	0.27		
TO	WTO accession; tariff cuts	21.5	Yes	0.44		
Panel F. Johansen Cointegration Tests						
Rank r	Trace Stat	5% Crit (Trace)	Decision (Trace)	Max-Eigen Stat	5% Crit (Max)	Decision (Max)
0	112.4	76.1	Reject	44.2	40.2	Reject
1	68.2	54.0	Reject	32.5	28.1	Reject
2	35.6	35.2	Reject	22.7	22.0	Reject
3	12.9	18.6	Fail to reject	8.9	15.8	Fail to reject
Panel G. Weak Exogeneity Tests for REC, FDI, TO (LCF equation)						
Variable	α_x (estimate)	LR χ^2	p-value	Decision (5%)		
REC	-0.21	5.92	0.015	Reject		
FDI	-0.07	1.76	0.184	Fail to reject		
TO	-0.18	4.87	0.027	Reject		
Panel H. Long-run Elasticities for LCF (VECM-DOLS and FMOLS)						
Regressor	DOLS coef	DOLS t-	FMOLS	FMOLS		
REC	0.342	3.21	0.361	3.45		
FDI	0.086	1.34	0.074	1.11		
TO	0.176	2.47	0.182	2.62		
Y	0.428	4.02	0.441	4.18		
Intercept	-1.215	-2.18	-1.143	-2.05		

Note: The superscript * denotes the level of significance at a 10% level.

The quantile-on-quantile results in Table 8 show state-dependent effects that vary across the joint distribution of the outcomes and exposures: for LCF, the REC surface rises with both the REC quantile (θ) and the LCF quantile (τ); the response is largest in the high-REC/high-LCF corner, with a positive $\theta \times \tau$ interaction. The LL–HH contrast was negative, confirming the stronger effects in the HH quadrant. The LH–HL contrast was slightly negative, indicating a greater role for REC intensity than for the outcome state when only one was high. The FDI→LCF effects are positive but shallow and flatten at upper quantiles, and the symmetry tests are near zero, indicating limited cross-state asymmetry. The TO→LCF peaks around the middle θ and remains positive across τ , reflecting stronger effects when trade openness is neither constrained nor extreme. The LL–HH gap remains negative but is smaller than that for the REC. For ILCF, REC effects also increase with both θ and τ ; the LH–HL contrast turns positive, indicating that a higher outcome state (τ) can dominate exposure intensity when REC is moderate. FDI→ILCF remains small across the surface with weak quadrant contrasts. TO→ILCF mirrored the LCF pattern with mid- θ strength and mild asymmetry. These patterns imply the need for targeted policies. Push REC when both deployment capacity and low-carbon performance are already elevated; marginal gains are highest in those states. Where TO sits near its middle quantiles, trade facilitation complements REC; at very low or very high TO, we expect a weaker pass-through effect. Given the shallow FDI surface, pair FDI policy with the REC and TO levers rather than relying solely on capital inflows.

Table 8. Quantile-on-Quantile Effects — All Panels (A–G).

Panel A. QQ summary statistics (mean/min/max of $\beta(\theta, \tau)$)			
Pair	Mean	Min.	Max.
REC->LCF	0.251	0.121	0.399
FDI->LCF	0.100	0.048	0.161
TO->LCF	0.143	0.072	0.223
REC->ILCF	0.223	0.103	0.362
FDI->ILCF	0.079	0.033	0.123
TO->ILCF	0.120	0.060	0.182
Panel B. REC → LCF — Quadrant means			
Quadrant	Mean β	SD	N cells
LL	0.185	0.035	25
LH	0.249	0.034	20
HL	0.262	0.035	20
HH	0.343	0.030	16
Contrast	Mean diff	SE (approx)	t-stat (approx)
LL - HH	-0.158	0.010	-15.55
LH - HL	-0.013	0.011	-1.19
Panel C. FDI → LCF — Quadrant means			
Quadrant	Mean β	SD	N cells
LL	0.073	0.014	25
LH	0.100	0.013	20
HL	0.106	0.016	20
HH	0.137	0.012	16
Panel C. FDI → LCF — Symmetry tests			
Contrast	Mean diff	SE (approx)	t-stat (approx)
LL - HH	-0.063	0.004	-15.52
LH - HL	-0.006	0.005	-1.42
Panel D. TO → LCF — Quadrant means			
Quadrant	Mean β	SD	N cells
LL	0.106	0.020	25
LH	0.144	0.020	20
HL	0.147	0.016	20
HH	0.192	0.016	16
Panel D. TO → LCF — Symmetry tests			
Contrast	Mean diff	SE (approx)	t-stat (approx)

LL - HH	-0.085	0.006	-15.26
LH - HL	-0.003	0.006	-0.56
Panel E. REC → ILCF — Quadrant means			
Quadrant	Mean β	SD	N cells
LL	0.160	0.032	25
LH	0.232	0.028	20
HL	0.223	0.033	20
HH	0.307	0.027	16
Panel E. REC → ILCF — Symmetry tests			
Contrast	Mean diff	SE (approx)	t-stat (approx)
LL - HH	-0.147	0.009	-15.66
LH - HL	0.008	0.010	0.84
Panel F. FDI → ILCF — Quadrant means			
Quadrant	Mean β	SD	N cells
LL	0.058	0.012	25
LH	0.078	0.010	20
HL	0.082	0.011	20
HH	0.108	0.009	16
Panel F. FDI → ILCF — Symmetry tests			
Contrast	Mean diff	SE (approx)	t-stat (approx)
LL - HH	-0.050	0.003	-15.16
LH - HL	-0.004	0.003	-1.20
Panel G. TO → ILCF — Quadrant means			
Quadrant	Mean β	SD	N cells
LL	0.091	0.017	25
LH	0.121	0.017	20
HL	0.124	0.013	20
HH	0.162	0.013	16
Panel G. TO → ILCF — Symmetry tests			
Contrast	Mean diff	SE (approx)	t-stat (approx)
LL - HH	-0.071	0.005	-15.03
LH - HL	-0.003	0.005	-0.71

4.4. Causality Assessment

Results Table 9 presents the findings from both the traditional Toda–Yamamoto (TY) causality test and the Fourier TY causality test examine directional linkages among key macroeconomic and environmental variables. The results provide subtle insights into the model's short-run and frequency-based causal interactions. Conventional Toda–Yamamoto (TY) causality tests suggest that the Load Capacity Factor (LCF) Granger-causes Renewable Energy Consumption (REC) and foreign direct investment (FDI) at the 1% significance level.

When environmental pressure intensifies, the response to renewable energy investment and foreign capital inflows is stronger. Nevertheless, the traditional model does not indicate that LCF causes trade openness (TO) or gross domestic product (GDP). Notably, TO Granger-causes LCF at the 1% level, implying that higher trade levels may lead to increased carbon emissions, likely due to industrial growth and trade activities that consume high energy levels. The Fourier TY test, which incorporates structural breaks and nonlinearity, provides additional information. It confirms bidirectional causality between LCF and FDI and reveals a significant relationship between LCF and GDP at the 1% level, illustrating the effects of environmental stress on economic output when time-varying dynamics are considered.

The TO-LCF relationship is significant in both tests, emphasizing the strong link between trade growth and environmental degradation. Conversely, the association between environmentally related variables, such as REC, FDI, and GDP, is statistically insignificant, indicating that environmental impacts are more sensitive to economic activity than vice versa.

Table 9. Results of causality assessment: TY causality and Fourier TY causality test.

Hypothesis	TY causality		Fourier TY causality		
	F Statistics	Significance	F Statistics	Significance	Frequency
LCF=>REC	8.901	***	6.215	**	3
LCF=>TO	1.142	-	1.317	-	3
LCF=>FDI	9.472	***	8.460	***	3
LCF=>Y	3.276	-	9.044	***	3
REC=>LCF	1.133	-	2.698	-	3
TO=>LCF	8.455	***	7.600	**	3
FDI=>LCF	3.076	-	4.323	-	3
Y=>LCF	2.836	-	3.027	-	3

Note: The superscripts ***, **, denote significance at the 1%/5%/ and 10% level (p-value <1%, 5%, 10%, respectively).

Hatemi-J-J tests and NARDL asymmetry point to directional, state-dependent transmission from energy and openness to carbon performance (Table 10). For LCF as the dependent variable, $REC^+ \rightarrow LCF$ and $TO^+ \rightarrow LCF$ pass the causality tests ($p=0.018$ and $p=0.031$, respectively), while REC^- , FDI^+/FDI^- , and TO^- do not ($p \geq 0.072$). For ILCF, both REC^+ and REC^- cause adjustment ($p=0.029$ and $p=0.049$, respectively), TO^+ is borderline at 10% ($p=0.052$), and FDI shocks remain non-causal ($p \geq 0.112$). The NARDL confirms these directions. With LCF, long-run and short-run asymmetry hold for REC (WLR $p=0.021$; WSR $p=0.012$) and TO (WLR $p=0.046$; WSR $p=0.049$), while FDI shows no asymmetry ($p > 0.10$). With ILCF, REC exhibits long- and short-run asymmetry (WLR $p=0.031$; WSR $p=0.023$), TO shows weak long-run asymmetry near the 10% level (WLR $p=0.069$), and FDI appears to be symmetric. These results imply that distinct operational levers exist.

Table 10. Asymmetric Causality and NARDL Asymmetry — Panels A–D.

Panel A. Hatemi-J Asymmetric Granger Causality — DV = LCF					
Exposure (shock)	VAR lag (AIC)	Wald χ^2	Bootstrap p	Decision (5%)	
REC ⁺	2	7.84	0.018	Reject H ₀	
REC ⁻	2	4.12	0.072	Fail to reject	
FDI ⁺	1	2.31	0.143	Fail to reject	
FDI ⁻	1	1.05	0.312	Fail to reject	
TO ⁺	2	6.03	0.031	Reject H ₀	
TO ⁻	2	3.77	0.089	Fail to reject	
Panel B. Hatemi-J Asymmetric Granger Causality — DV = ILCF					
Exposure (shock)	VAR lag (AIC)	Wald χ^2	Bootstrap p	Decision (5%)	
REC ⁺	2	6.91	0.029	Reject H ₀	
REC ⁻	1	5.02	0.049	Reject H ₀	
FDI ⁺	1	1.74	0.187	Fail to reject	
FDI ⁻	1	1.28	0.266	Fail to reject	
TO ⁺	2	4.96	0.052	Borderline (10%)	
TO ⁻	2	3.21	0.112	Fail to reject	
Panel C. NARDL Asymmetry Tests — DV = LCF					
Regressor	WLR (F)	p (WLR)	WSR (χ^2)	p (WSR)	Decision
REC	5.72	0.021	6.35	0.012	LR & SR asym present
FDI	1.64	0.204	2.07	0.151	No clear asymmetry
TO	4.11	0.046	3.88	0.049	LR & SR asym present
Panel D. NARDL Asymmetry Tests — DV = ILCF					
Regressor	WLR (F)	p (WLR)	WSR (χ^2)	p (WSR)	Decision
REC	4.86	0.031	5.18	0.023	LR & SR asym present
FDI	1.22	0.273	1.58	0.209	No clear asymmetry
TO	3.41	0.069	2.92	0.087	Weak LR asym (10%)

The LCF responds to upside shifts in renewables and trade openness but not to downside movements within the sample dynamics. Design policies that prioritise accelerating renewable deployment and trade facilitation to enhance the impact of LCF. ILCF adjusts to both REC⁺ and REC⁻; therefore, planning should address expansion and pullback phases and build mechanisms to sustain investment when REC momentum slows and scale capacity when REC rises. FDI does not display causal or asymmetric effects in either equation; it treats capital inflows as supportive rather than as the primary driver of near-term carbon outcomes. For modelling, we kept positive/negative partial sums for REC and TO, estimated separate adjustment paths, and reported long- and short-run Wald tests alongside Hatemi-J p-values. For forecasting and stress testing, we run scenarios that toggle REC and TO in the positive domain for LCF and in both domains for ILCF, while holding FDI shocks as symmetric disturbances. Align policy narratives and robustness checks with the directional features.

4.5. Robustness Assessment

The Enders–Siklos tests, see results in Table 11, indicate threshold cointegration for both equations and regime-dependent correction speeds. For LCF with TAR, the null of no threshold cointegration is rejected ($\Phi=9.86$, $p=0.012$). The adjustment is asymmetric: when the lagged error exceeds the threshold ($\gamma = 0.12$), the error correction coefficient equals -0.31 with a half-life of approximately 1.9 periods; when it does not, the coefficient equals -0.08 with a half-life of approximately 8.3 periods. The symmetry test rejected the equality of speeds ($\Psi=5.23$, $p=0.028$). The M-TAR variant also rejects no threshold ($\Phi=7.45$, $p=0.022$) and rejects symmetry ($\Psi=4.10$, $p=0.043$); momentum matters, with faster correction under positive error-momentum ($\rho=-0.28$; half-life ≈ 2.1) than under negative momentum ($\rho=-0.06$; half-life ≈ 11.2).

Table 11. Threshold Cointegration and EKC.

Panel A. Enders–Siklos TAR — DV = LCF							
Regime	ρ	SE(ρ)	t-stat	γ	Upper HL	Lower HL	
Upper ($EC_{-1} > \gamma$)	-0.31	0.11	-2.82	0.12	1.87	8.31	
Lower ($EC_{-1} \leq \gamma$)	-0.08	0.09	-0.89				
Φ ($\varphi_1=\varphi_2=0$)	9.86	Boot p(Φ)	0.012	Ψ ($\varphi_1=\varphi_2$)	5.23	Boot p(Ψ): 0.028	
Panel B. Enders–Siklos M-TAR — DV = LCF							
Regime	ρ	SE(ρ)	t-stat	γ	Upper HL	Lower HL	
Momentum upper ($\Delta EC_{-1} > \gamma$)	-0.28	0.1	-2.8	-0.01	2.11	11.2	
Momentum lower ($\Delta EC_{-1} \leq \gamma$)	-0.06	0.08	-0.77				
Φ ($\varphi_1=\varphi_2=0$)	7.45	Boot p(Φ)	0.022	Ψ ($\varphi_1=\varphi_2$)	4.1	Boot p(Ψ): 0.043	
Panel C. Enders–Siklos TAR — DV = ILCF							
Regime	ρ	SE(ρ)	t-stat	γ	Upper HL	Lower HL	
Upper ($EC_{-1} > \gamma$)	-0.22	0.1	-2.2	0.09	2.79	6.58	
Lower ($EC_{-1} \leq \gamma$)	-0.1	0.08	-1.25				
Φ ($\varphi_1=\varphi_2=0$)	6.12	Boot p(Φ)	0.041	Ψ ($\varphi_1=\varphi_2$)	2.35	Boot p(Ψ): 0.126	
Panel D. Enders–Siklos M-TAR — DV = ILCF							
Regime	ρ	SE(ρ)	t-stat	γ	Upper HL	Lower HL	
Momentum upper ($\Delta EC_{-1} > \gamma$)	-0.24	0.11	-2.18	0.0	2.53	9.55	
Momentum lower ($\Delta EC_{-1} \leq \gamma$)	-0.07	0.08	-0.88				
Φ ($\varphi_1=\varphi_2=0$)	8.02	Boot p(Φ)	0.019	Ψ ($\varphi_1=\varphi_2$)	3.86	Boot p(Ψ): 0.05	
Panel E. Hansen GDP-per-capita Threshold — EKC within LCF equation							
	GDP threshold (log)	95% CI (log)	Sup-Wald	Boot p	Slope below	Slope above	Level approx.
	9.65	[9.44, 9.87]	12.8	0.018	0.112	-0.076	15521

For ILCF, TAR rejected no threshold ($\Phi=6.12$, $p=0.041$) but did not reject symmetry ($\Psi=2.35$, $p=0.126$). Speeds still differ in magnitude: upper regime $\rho=-0.22$ (half-life ≈ 2.8) and lower regime $\rho=-0.10$ (half-life ≈ 6.6). The M-TAR specification rejects no threshold ($\Phi=8.02$, $p=0.019$) and yields a borderline symmetry result ($\Psi=3.86$, $p=0.050$); momentum asymmetry appears with $\rho=-0.24$ (half-life ≈ 2.6) in the upper momentum regime and $\rho=-0.07$ (half-life ≈ 9.9) in the lower momentum regime. Within the LCF equation, the Hansen single-threshold model in log GDP per

capita identifies an endogenous turning point at 9.65 (95% CI [9.44, 9.87]), and the sup-Wald test rejects linearity (12.8; $p=0.018$). The slope below the threshold is positive (0.112), and the slope above is negative (-0.076), implying an inverted U-shaped income-LCF relationship. Implications for modelling include incorporating regime indicators into the error correction mechanism, reporting regime-specific speeds and half-lives, and utilising momentum thresholds where appropriate. Policy design implications: Target interventions that prevent persistence in the slow-adjustment regime, prioritise actions that move the system into the fast-adjustment regime, and align income-linked measures with the identified GDP threshold to avoid deterioration beyond the turning point.

5. DISCUSSION

The results of this study confirm that the share of renewable energy in energy mixes and proximity to environmental sustainability are positively related, aligning with emerging empirical evidence about system-transformative impacts from clean energy transitions. The findings contribute to the growing debate on the energy-environment nexus and provide policymakers with insights into strategic pathways for sustainable development. However, our results are in line with those predicted by Croutzet and Dabbous (2021) and Cui, Weng, and Song (2022). A regional environmental efficiency study on the growth of renewable energy in Brazil found an inverse relationship between CO₂ emissions and renewable energy consumption, suggesting a negative effect. These findings also parallel previous multi-country-level studies that reported similar results in new areas in other countries from different parts of the world. The strength of this relationship is striking, considering that studies comprising only OECD countries have projected a lowering of the CO₂ emissions of the power sector amounting to 7.4% in year 2 following an increase in renewable energy (versus a fall of approximately 10% over 2 years and around 5% after five years). This time perspective makes the connection between these present benefits and future ones obvious and is consistent with previous controversies about whether the environmental benefits of renewable energy penetration are short-term only or also long-term, and likewise, whether clean transitions make sense. Renewable energy directly substitutes for electricity generated by burning fossil fuels, which account for more than 75% of global greenhouse gas emissions. Second, the life-cycle emissions (from manufacturing, installation, and operation) of renewable technologies are significantly lower than those of fossil fuels. An examination of 138 countries over more than two decades, from 1990 to 2017, found that in locations where a country added renewable energy capacity, carbon dioxide emissions were at least half as low 4 years later, as Swanson's Law suggests. In addition to the carbon mitigation effect, our study proposes that including renewable energy input, particularly wind and solar (as given in monitoring total environmental figures such as LCF and EF), could be advantageous for EQ at large. An empirical analysis of the G-20 countries reveals that renewables reduce both long- and short-run ecological footprints, thereby improving environmental quality. Nevertheless, multifaceted positive environmental feedback loops (e.g., improved air quality, reduced water pollution, or decreased soil erosion) may not be fully accounted for by calculating carbon particle-induced parameters alone.

The results suggest a negative impact of FDI on environmental sustainability, indicating that FDI exacerbates environmental degradation in Bangladesh. This conclusion is supported by the gradually accumulating empirical evidence for the pollution haven hypothesis, based on data from Bangladesh, which highlights a disconcerting trend: investment inflows triggered by Foreign Direct Investment contribute to the depletion of environmental quality, rather than serving as equalizers. The findings overwhelmingly support the PHH model in Bangladesh. Studies reveal that FDI inflows are heavily pollution-oriented, being transferred from a cleaner-haven home country to a relatively less stringent host country, such as Bangladesh. The detrimental impact of FDI on environmental quality suggests that the Indian firm, by bribing, has taken advantage of the recipient country's (Bangladesh) environmental weakness, and the transfer of polluting technology is also occurring. This is indicative of a vicious cycle where 'loose' environmental policy is not deterring but rather attracting environmentally degrading FDI. By this measure, the industry with which we have made the most embarrassing mistake is high FDI-attracting textiles. The foreign- and

joint venture-owned textile plants could be considered the primary sources of water pollution because tanneries have been discharging untreated effluent into rivers, contaminating them with heavy metals and toxins. These reports confirm that most textile dyeing factories lack functioning ETPs or intentionally circumvent treatment stations to reduce production costs. They provide insights into how foreign investment in Bangladesh exacerbates, rather than alleviates, environmental problems.

Regarding technology spillover effects, the results reveal that FDI has not led to environmental improvements due to insufficient technology diffusion. While some proponents of FDI like to discuss "pollution halo" effects on newer, clean technologies, the Bangladesh episode suggests otherwise: Instead of clean, state-of-the-art means of production, international investors are bringing outdated, pollution-prone technology. Such leakage of technology transfer is consistent with the strategic decision of multinational companies to relocate production from an older, more carbon-intensive plant to a country with weaker environmental regulations. In Bangladesh, weak or corrupt institutions and low-level enforcement lead to significant environmentally harmful FDI. Moreover, the DoE also has structural governance failures, and such deficiencies are bureaucratic dependence, other than a lack of modern monitoring instruments and professional ineptness.

Most importantly, corruption is embedded in the country's environmental institutions, as government officials partner with polluters and foreign investors to work around Brazil's already weak environmental laws. These difficulties are exacerbated by the slow pace of the legal process and the uncertain enforceability of contracts, as environmental offenses often carry few penalties. Because there is little enforcement of the law, and huge amounts of money to be made here, a foreign corporately owned business will receive its respective government monitoring and operate unfettered, and continue its destruction. The textile industry is the largest recipient of manufacturing FDI in Bangladesh and can serve as an example of how foreign capital has exacerbated environmental degradation. Textile factories owned by foreign companies are consistently among the country's worst polluters. Studies have found that some of the world's largest multinationals have emerged as leading contributors to both plastic pollution and water contamination in the country. The sector's water footprint stands at 1.8 billion cubic meters per year, with textile dyeing units discharging untreated effluents containing chromium, lead, and other heavy metals into water bodies.

Although foreign textile companies are required to install ETPs, they bypass environmental standards in several ways. These include purchasing treatment equipment without operating it, importing inferior technology, and gaming the rules. The end product has led to rampant pollution of the country's most important rivers, such as the Buriganga, Dhaleshwari, and Turag, which have all become "biologically dead" because no aquatic life can survive industrial pollution. Given the harmful impact of FDI in Bangladesh, the existing policy on attracting foreign investments needs to be critically rethought. The environmental effects of policy-induced trade liberalization operate through several interrelated channels, resulting in a range of outcomes that vary across countries and over time. The channel of competitiveness is that more stringent policies will raise production costs across countries relative to less demanding countries, leading to a loss of competitiveness and the allocation of higher-polluting activities to pollution havens. Recent evidence from MENA region countries that combined the three variables showed strong long-run relationships among trade openness, FDI, electricity use, and CO₂ emissions for the cointegrated relationship such that, in the long run, trade openness brings about emission reductions; however, short-run coefficients differ (Gorus & Aydin, 2019; Nathaniel et al., 2020; Xiangling & Qamruzzaman, 2024). The technology transfer channel acts as a counteractive force by facilitating trade that promotes the spillover of cleaner technologies and production processes from industrialized to developing countries. Technological innovation in manufacturing enhances sustainability by increasing the efficiency of industrial processes. Between 2025 and beyond, cleaner technological innovation has consistently decreased CO₂ emissions and ecological footprints in BRICS+T countries. Nevertheless, the paper also finds (Chien, Paramaiah, Pham, Phan, & Ngo, 2023; Hoa et al., 2024; Javed et al., 2023; Qamruzzaman, 2025). Trade openness has a double-edged effect: it improves resource-use efficiency but also increases CO₂ emissions and ecological footprints, given limited technology-absorptive capacity to fully master advanced green technologies

(Cutcu et al., 2023; Guo et al., 2023; Lu, 2020; Okelele et al., 2022). An analysis conducted in 2024 that separated these effects found that compositional (structural) changes, such as a shift toward less pollution-intensive industries, may mitigate the environmental impact of trading activity; however, the scale of the economy seems to prevail, at least in developing countries. These dynamics are influenced by export diversification and product concentration, as research shows that higher levels of export market diversification and export product diversification are associated with lower CO₂ emissions through composition effects that result in production shifting toward less pollution-intensive products (Udeagha & Breitenbach, 2023; Wang et al., 2024).

Recent advances in econometrics suggest that threshold and nonlinear effects characterise the trade-environment linkage. An investigation of African countries through double threshold models, Aydin and Turan (2020) and Bayer and Hanck (2013) found complex, non-linear effects of trade openness on CO₂ emissions, with its influence varying from one emission quantile to another. In another example, an investigation of Aydin and Turan (2020); Bayer and Hanck (2013) and Hasan and Chongbo (2020) dealing with Belt and Road countries in the period 2001–2019 using panel quantile regression also revealed heterogeneity in the trade openness effect on carbon emissions, where it was strongly dependent on how much a given country emitted, and the impacts varied greatly between countries. These results suggest that one-size-fits-all policy recommendations, particularly regarding trade openness, are insufficient, given the importance of country-specific prescriptions for baseline emission levels, institutional capabilities, and stages of development. Studies examining the threshold effects between natural resource rents and the control of corruption have shown that significant threshold effects exist between trade openness and environmental quality in developing countries (Marques & Caetano, 2020; Munjer et al., 2023; Musah, 2022). The results reveal that at institutional quality levels below certain thresholds, trade openness has a detrimental impact on environmental quality, whereas at levels above these thresholds, it has a positive effect. This evidence underscores the crucial role of governance quality and institutional structures in determining whether trade liberalization yields environmental benefits or drawbacks.

6. CONCLUSION AND POLICY SUGGESTION

6.1. Conclusion

The current study offers a detailed and well-referenced insight into the asymmetric and non-linear relationships between renewable energy consumption, foreign direct investment (FDI), trade openness, and environmental sustainability in Bangladesh, utilizing a unique Load Capacity Factor (LCF) and its inverse indicator, ILCF. The use of Fourier ARDL and NARDL models, combined with sophisticated causal frameworks such as the Fourier Toda–Yamamoto approach and time-dependent parameter VAR, provides insight into both long- and short-run dynamics, structural breaks, and state-dependent effects. The findings of our study also support the EKC hypothesis in LCF and ILCF; that is, economic growth initially degrades eco-capacity but helps restore it to a high level of income. The NARDL and quantile-on-quantile models confirm that renewable energy use is a significant positive contributor to sustainability, as evidenced by increasing elasticities. FDI is, in turn, associated with reduced ecological capacity across the full range of the sample, and FDI booms and busts have heightened rather than reduced environmental stress, indicating that 'dirty' investments dominate over green inflows. Trade intensity also shows a negative association with LCF, particularly during recessions, with the beneficial effects conditional on middle quantile status and sound governance. These results align with the pollution haven and trade–environment paradox hypotheses, revealing the underlying structural weakness of Bangladesh's current development path.

6.2. Policy Suggestions

A sensible, contextually relevant policy agenda is needed, drawing on the empirical evidence and methodological achievements of this study to guide Bangladesh toward environmentally sustainable development. First and foremost, we need to make the inspiring concept of renewable energy, beautiful on paper and hope-giving when politicians

speak of it, a down-to-earth subject matter for economic and regulatory policy. The striking asymmetric long-run elasticity of REC over LCF6 and its key role in mitigating ILCF suggest that sustainable investments in renewables generate de facto excessive environmental benefits. The 2015 Renewable Energy Policy (2025) targets set by the government must be revised upward by providing performance-based incentives, introducing cost-reflective feed-in tariffs, and creating risk-reduction tools such as green bonds and currency hedging facilities. Investing in such areas should be directed to the same regions and sectors identified in the quantile-on-quantile analysis as high-impact zones, especially where REC deployment potential is strong and ecological resilience is relatively high. On this scale, public-private partnerships and blended finance facilities must be used to generate the necessary US\$980 million annually by 2030 (\$1.46 billion thereafter). At the institutional level, incorporating the REC into planning frameworks for macro-level developmental strategies, such as the Five-Year Plans, will help embed it in institutions as a central development actor rather than an appendage.

Second, a strategic reset of the foreign direct investment policy is required. The negative FDI LCF elasticity and flat response surface in all states illustrate the dominance of carbon-intensive investment inflows. To reintegrate FDI with environmental objectives, a green screening mechanism should be incorporated into the investment approval process, coupled with compulsory environmental impact assessments, post-investment audits, and incentives for low-carbon technologies. Green FDI should be categorized, and sector-specific guidelines should be issued by the Bangladesh Investment Development Authority (BIDA). The framework should be monitored through a joint conformance framework with the MOEF. Simultaneously, the “pollution halo” can be unlocked thanks to targeted co-investment in innovation clusters, university-industry linkages, and technology transfer hubs along renewable technologies.

Third, trade policy must combine the twin objectives of supporting technology transfer and protecting against environmental externalities associated with an open economy. The asymmetrical effects of trade openness and larger losses during contractions mean that durable, rules-based trade governance is a priority. Bangladesh could subscribe to trade agreements with environmental conditionalities, establish a common sustainability standard, and reward exporters for cleaner production through export waivers or certificates. The significant mid-quantile trade openness effects on LCF imply a midway trade facilitation: focus only on sectors where size and technique effects can be reconciled, namely electronics, textiles, and agri-processing. Border carbon adjustments and eco-labeling initiatives can be combined to protect domestic green sectors from leakage while promoting international competition. Future research directions.

Notwithstanding the strength of these empirical results, this analysis has some obvious limitations and offers directions for future research. First, although LCF and ILCF provide a more comprehensive overview of ecological capacity than conventional emission-based indicators, they remain national or regional mean measures that may smooth over intraregional differences and sector-specific disparities. The study may serve as a basis for incorporating spatially disaggregated data or utilizing environmental indicators derived from satellite data in sub-national level analysis. Second, the paper's focus on annual macroeconomic data (albeit comparable across all countries and policy-relevant) may limit the ability to detect short-run volatility or rapid policy feedback effects; it neither allows for exploring sensitivity around the results nor supports the study of volatile equilibria and resilience mechanisms. Third, while the empirical models incorporate structural breaks and nonlinearity in their specifications, they have yet to be well integrated with political economy variables such as regulatory quality, institutional integrity, and fiscal transparency. The introduction of governance determinants may uncover important intermediate interaction effects between economic activity and environmental sustainability.

Furthermore, social factors such as public knowledge, symbiosis with civil society, and media promotion can be incorporated into future models to supplement the economic drivers investigated here quantitatively. Fourth, while the study identifies the policy relevance of elasticities and causality findings, additional micro-level research on firm behavior, energy price structures, and investment incentives would yield more nuanced recommendations. Finally,

the correlation between REC, FDI, and TO suggests potentially endogenous co-evolution, which may be addressed through structural macroeconomic models or agent-based simulations.

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