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RESEARCH ARTICLE

Green Energy and Technological Innovation Toward a Low-Carbon Economy in Bangladesh

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Abstract: This study aims to investigate the influences of green energy, technological innovation, economic growth, urbanization, and labor force on the low-carbon economy in Bangladesh. Bangladesh was chosen for this study as the country in the sixth most vulnerable nation, and the results of climate change on the country's ecology and economy have been devastating. By using yearly data extending from 1990 to 2020, this research employed the autoregressive distributed lag (ARDL) technique to explore the connections between explained and explanatory factors across both the short and long term. The ARDL bounds test decisions pointed to a long-term connection between the variables. The empirical results revealed that a 1% increase in economic growth, urbanization, and labor force would lead to 1.09%, 1.14%, and 0.19% increase in carbon economy in the long run, while 1.67%, 1.50%, and 0.29% increase in the short run, respectively. However, the findings indicated that a 1% boost in green energy utilization and technology innovation would result in a 0.21% and 0.18% decline in the carbon economy in the long run, whereas 0.15% and 0.10% drop in the short run, respectively. The outcomes of the investigation demonstrated that economic growth, urbanization, and labor force all adversely impact the low-carbon economy, making green energy utilization and technological innovation the best crucial approaches to maintain environmental sustainability. The study's findings specify a policy structure for developing a thorough tactic to stimulate environmental sustainability in Bangladesh, with a focus on ecological innovation, green energy utilization, and controlled urbanization. This article put forward policy implications aimed at a low-carbon economy, promoting green energy use, financing technological advancement, sustainable urbanization, and educating the labor force, to achieve environmental sustainability and emission reduction in Bangladesh.

Keywords: low-carbon economy, green energy, technological innovation, environmental sustainability

1. Introduction

Decarbonizing human civilization is the foundation for combating climate change catastrophe and ensuring ecological sustainability in the approaching years [1]. This is notably true in light of the fact that global warming has become a severe challenge triggered by the unbelievable surge in carbon emissions [2, 3]. With only 2 Gt in 1990, global energy-associated CO_2 emissions are presumed to emerge to nearly 36.8 Gt in 2022 [4]. Therefore, countries around the world will need to manage carbon emissions in order to maintain economic growth [5, 6]. This will help them accomplish the worldwide goal of sustainable development as well. Concurrently, the international community and individual governments are working on plans to realize carbon neutrality and the sustainable development goals (SDGs), despite the fact that global emissions are on the rise [7]. The UN's sixth policy brief study outlined the value of eco-friendly innovation and the benefits of investing in disruptive energy technologies [8]. Similarly, SDG-7 places greater focus on providing investments in affordable and clean energy so that the world's aspiration for a low-carbon economy can be realized [9].

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Therefore, the goal of sustainable development is to ensure the well-being of future generations by developing environmentally friendly, economically viable, and socially just technological solutions [10].

Bangladesh is the globe's fifth-fastest expanding economy and the second-fastest extending economy in South Asia [11]. Energy utilization has multiplied intensely as the industrial sector has switched to farming as the key economic carter in Bangladesh [12]. In recent years, energy consumption has been a major contributor to Bangladesh's economic growth. According to the World Bank [11], fossil fuels are reported for 74% of Bangladesh's overall energy consumption. CO_2 emissions due to the ignition of fossil fuels in Bangladesh are on the rise alongside the extension of economic pursuits and industrialization. As of 2020, the country's CO_2 emissions were close to 100 million tons [11]. The country is currently falling short of its targets (such as energy access, improving energy efficiency, and expanding renewables), so the strategy and financing must undergo fundamental shifts. These shifts include the adoption of low-carbon technologies throughout the manufacturing progression, the promotion of sustainable urbanization through careful municipal plotting, and the promotion of green stashes in the power segment [12]. Substituting clean energy resources like hydro, wind, and solar for harmful power resources like coal, oil, and gas in the manufacturing procedure safeguards environmental sustainability and macroeconomic presentation of the countries by lowering carbon emissions, decreasing dependence on imported fossil fuels, and relieving the burden on the steadiness of expenditures [13]. Therefore, countries around the world have recognized the importance of green energy by adopting policies like the Kyoto Agreement, which requires signatory nations to lessen their carbon emissions and upsurge the usage of renewable resources in industrial processes [5, 14]. This goal is also reflected in Agenda 2030's SDG 7, which is titled "affordable and clean energy."

Growing populations increased industrial development, and prompt urbanization in developing nations poses significant challenges to the switch to a low-carbon economy [15]. Reduced reliance on natural reserves like biomass, coal, natural gas, and oil for power requirements is a hallmark of eco-friendly technological innovation, which in turn ensures sustainable environmental and economic development [16]. This is due to the fact that the production of energy in most developing countries requires the exploitation of natural reserves, which has a detrimental effects on the ecosystem in the way of climate change [17]. The perception of a low-carbon economy can become a reality with the support of green technology developments, which not only foster inexpensive and environmentally friendly technologies but also lower the loss of ecological sustainability [18]. This, in turn, increases manufacture effectiveness and conserves natural resources by lowering CO_2 emissions [19], thus, green technological innovations are recognized as a key driver of a low-carbon economy in SDG 9's "industry, innovation, and infrastructure" category.

Massive urbanization is the most contentious issue of the modern era because it unbalances the connection between people and ecosystems in both advanced and emerging nations through, for example, increasing the number of automobiles in urban zones, snowballing urban flocking, increasing burdens on municipal sewerage and waste management systems, and increasing the effects of urban heat islands [20]. No universal rule exists to prevent people from migrating from countryside zones to municipal hubs since metropolitan areas offer better employment, education, and healthcare opportunities [12]. Approximately 77% of all greenhouse gas (GHG) emissions come from urban areas, making them the epicenter of economic activity and resource consumption [21]. By the end of 2022, about 57% of the earth's populace was residing in urban settings [11]. From 4.2 to 6.4 billion people, or roughly 68% of the earth's populace, will reside in metropolises by 2022 [22]. More than 40% of Bangladesh's population now resides in urban areas, up dramatically from just 8% in 1972 [11] with a yearly average urban inhabitant's expansion ratio of 1%. This rate of urbanization is causing significant ecological problems in Bangladesh.

In light of the aforementioned, the objective of this research is to examine the influences of technological improvement, economic expansion, labor force, urbanization, and the use of green energy resources on Bangladesh's low-carbon economy. Bangladesh was chosen for this study for a number of reasons. According to the Global Climate Risk Index 2022, Bangladesh is the sixth most vulnerable nation in the world to climate change and extreme weather events. Between 1996 and 2015, 185 weather-related disasters in Bangladesh caused the deaths of nearly 700 individuals. Bangladesh loses roughly $1 billion per year due to average tropical cyclone damage. By 2050, internal climate migration might affect 13 million people and cost the agriculture sector a third of its GDP. If floods are particularly severe, they might reduce GDP by as much as 9%. One of the greatest mass migrations in human history may result from climate change in Bangladesh, according to scientific estimates. In addition, energy use in Bangladesh has been on the rise in recent decades, and this trend is anticipated to continue. Large-scale industrial expansion, increasing urbanization, and a burgeoning population have all contributed to a rise in the nation's overall energy demand in recent times [12]. Despite a clear transition to a more sustainable energy system and a large potential for renewable resources, Bangladesh continues to rely on fossil fuels to meet its energy demands. World Bank data for 2023 show that barely 28% of Bangladesh's energy came from renewables in 2020. However, Bangladesh's government has committed to sourcing 40% of its power from renewable resources by 2041. Bangladesh has sworn to lessen emissions by 21.8% between 2020 and 2030 as part of its Nationally Determined Contributions (NDCs) for COP22. Bangladesh has the potential to go above and beyond these pledges with effective implementation, the invention and implementation of technological resolutions, and regional cooperation. Accordingly, Bangladesh needs to make adjustments to its energy policy and financing if it is to have any hope of fulfilling its NDC ambitions.

There are a number of ways in which this investigation contributes to the research in environmental economics. To begin, although a small number of academics in Bangladesh have scrutinized the connection between CO_2 emissions, green energy consumption, and technical advancements, no studies have examined this relationship using the current and low-carbon economy framework. This study established a proxy variable low-carbon economy to attain ecological loss because of economic expansion in Bangladesh by dividing CO_2 emission by one unit of production. This investigation is the pioneer effort to analyze the effects of different environmental influences on the low-carbon economy in the perspective of Bangladesh which fills a gap in the preceding academic works. Second, this research is different from others since it makes utilization of the utmost newfangled time series dataset and econometric methodologies to produce a comprehensive record of the literature on the low-carbon economy. The autoregressive distributed lag (ARDL) technique was applied to investigate both the long- and short-run impacts of the environmental factors on the low-carbon economy. Discussions regarding environmentally responsible behaviors should benefit by comparing their long- and short-run effects. Besides, multiple diagnostic procedures were also spawned to confirm the exactitude of the results. Third, the outcomes of this research provide legislators in Bangladesh with more thorough and relevant guidelines for creating efficient strategies in the fields of a low-carbon economy, fostering green energy usage, supporting technological innovation, and environmentally friendly urbanization, all of which are crucial to the nation's objectives of reducing emissions and environmental sustainability.

Moreover, this study's findings may help Bangladesh adjust policy in a way that better advances the SDGs. This may have an immediate impact on goals related to access to affordable and clean energy (SDG 7), inclusive and sustainable urbanization (SDG 11), innovative and sustainable technology (SDG 9), and reducing GHG emissions (SDG 13). At the policy level, the study contributes by exploring the connection between green energy, eco-friendly technological innovation, urbanization, and a low-carbon economy, which is central to the SDGs. In addition, the findings of this study can be applied to the assessment and development of environmental policies to help prepare Bangladesh for a 1.5 °C world by strengthening policy and action plans to mitigate the consequences of climate change and ensure sustainable development. This study's findings might be valuable for other developing nations seeking to strengthen their own climate change mitigation and adaptation strategies while dreaming of achieving a green and low-carbon economy.

2. Literature Review

The ecological footprint and CO_2 emissions are two of the utmost commonly applied proxies of environmental sustainability in the environmental economics literature. The concept of a low-carbon economy, also known as environmental sustainability, is an alternative to the "carbon economy" paradigm, which describes an economy that relies on traditional, harmful resources for power generation. According to this theory, GHG emissions should be retained at the minimal throughout the manufacturing procedure [23, 24] and the frequency at which natural resources are used up ought to be less than the ratio at which they are renewed [19]. Economic expansion, foreign direct investment (FDI), financial development, trade openness, fossil fuel energy use, rapid urbanization, and population expansion may affect environmental sustainability [25].

Alper and Oguz [26] in European countries, Ahmed et al. [27] in China, Sbia et al. [28] in the UAE, and Hao et al. [18] in G-7 nations are just a few of the many researchers who have discovered a favorable and noteworthy influence of green power resources on GDP growth. Green energy consumption has been shown to enhance ecological excellence in the literature. According to Wang and Dong's [29] analysis of 14 nations in sub-Saharan Africa, the utilization of renewable power sources has significantly enhanced environmental quality by lowering the regional ecological trajectory. Destek and Sinha [30] found similar results for the OECD economies and the African continent, demonstrating the large positive effect of green energy use on environmental conditions in both regions. By lowering carbon dioxide emissions, green energy utilization promotes environmental sustainability [31]. Analogous assumptions were rendered by Sharif et al. [32] for the Turkish economy. Almost all of the empirical investigation that examine the association between renewable power usage and environmental attribute revealed a favorable correlation between the two.

Concurrently, a variety of approaches are employed to identify the ways in which technological developments contribute to environmental degradation. Both the IPAT and STIRPAT models consider the influences of monetary and industrial possessions on ecological well-being. In accordance with several studies [33, 34], progress in green energy technology can improve environmental appropriateness without slowing economic growth. The positive and statistically significant link concerning green technology developments and green economic expansion has been demonstrated by a number of empirical research [34]. Sohag et al. [35] highlighted the importance of reworking monetary markets to support sustainable development and environmentally friendly technologies. The best way to improve people's attributes of life and safeguard the sustainability of society, in the long run, is to invest in technological innovation [34, 36]. Green technological innovations contribute to green economic growth by addressing a variety of environmental issues, such as the reduction of carbon dioxide emissions, as stated by Ahmad et al. [37] from the prospect of South Asian nations. Padilla-Pérez and Gaudin [38] discovered a similar significantly positive liaison involving green economic development and research, technology, and innovation in Central American countries. Transforming the energy sector and decreasing CO_2 emissions are two ways in which green technical breakthroughs positively contribute to sustainable development [39]. Companies that invest in environmentally benign technologies should be subsidized, while those that contribute to pollution should be taxed [40, 41].

The consequences of urbanization on environmental sustainability have been the subject of numerous studies, with widely varying results. Ahmed et al. [27] discovered that urbanization, combined with FDI, drives ecological degradation. Khan et al. [42] ran dynamic ARDL model for the context of Pakistan and showed that while urbanization and CO_2 emissions were positively linked in the short run, this synergy diminished with time. Countries experiencing faster economic growth rates as a consequence of industrialization and urbanization face environmental deprivation [43]. While there was a significantly negative link concerning globalization, urbanization, and ecological degradation, a study by Haseeb et al. [44] discovered that energy use and commercial expansion positively impacted ecological deterioration from the perspective of BRICS territories. Likewise, Huang and Wang [45] found that urbanization and fossil fuels were the primary causes of environmental deprivation in the Chinese economy. Urbanization is favorably accompanied by the emissions of CO_2 in the circumstances of rich and upper-middle-income countries, while it has a bad consequence on environmental conditions in low- and middle-income economies [6].

Briefly, the importance of green energy innovation in justifying the low-carbon economy was overlooked in the empirical investigation of the connection between energy–innovation–urbanization. In contrast, the present research stands in for green innovation with the number of patents. However, none of the previous studies have looked at the connection in a Bangladesh-specific setting. Urbanization and the consumption of renewable energy resources were also overlooked in environmental policy analyses. Despite the relevance of the growth–emissions relationship, most of the experiments sourced energy usage as a means of linking the factors, and in a limited circumstance, researchers neglected to account for the role that innovation and other critical drivers played. Specifically for Bangladeshi situations, this research will fill in the blanks that have never before been investigated comprehensively in a single study.

3. Methodology

3.1. Theoretical framework

The "environmental Kuznets curve" (EKC) method is commonly utilized in the field of ecological economics to establish the connection between economic expansion and ecological deprivation. The EKC theory proposed a backwards-U relationship between rising prosperity and deteriorating ecosystems over time. This means that up to a certain point in GDP growth, environmental degradation grows in developing countries. This is because rising production levels necessitate more raw resources, which in turn boosts economic activity and worsens environmental quality. Positive correlations are observed between green energy usage and innovation in environmentally friendly policy later on [41, 46], as the ecological condition improves because of these practices and the reduction of other pollutants. Over age, commercial expansion in an economy that relies heavily on output affects ecological quality in three ways, as described by Dinda [47]. The first level corresponds to a subsistence economy, which engages in minimal production and hence generates less emissions. As production activities grow up, more fossil fuels and other raw materials are needed, degrading ecological quality in the subsequent segment of economic expansion. The implementation of eco-friendly technology and the swap of fossil energy resources for cleaner energy resources in the manufacturing process allow countries to improve environmental quality and reduce environmental degradation via the method effect.

Three primary theories – the urban environment transition (UET), the compact city (CC), and the ecological modernization (EM) theory – provide the theoretical foundation for explaining the link between a weak economy and urbanization [48]. Increased intake of natural possessions, stresses on metropolitan sewage and cleanliness arrangements, and overcapacity all have negative effects on ecological quality due to increased emissions of carbon dioxide, as postulated by the UET and CC [49]. But proponents of the EM theory counter that environmental issues change with the economy, arguing, for instance, that a greater mandate for harmful energy usage in the manufacturing procedure increases CO_2 emissions, but that as the economy develops, ecological quality improves, thanks to stringent environmental laws, green technological innovations, and the transition to renewable power resources. Urbanization has harmful effects on the environment, but these effects can be lessened via careful planning and attention to sustainability [50]. Hence, it is tough to launch some sort of theoretical connection between a low-carbon economy and urbanization due to the availability of contradictory literature concerning the nexus between the two; thus, experiential indication is required to launch any kind of interaction amid the factors. Green energy utilization and green innovations in renewable power production (solar, wind, biomass, and thermal) are key to realizing the vision of a low-carbon economy [51]. These measures significantly cut CO_2 emissions and slow down the worsening of the environment by decreasing the usage of fossil fuels (coal, oil, gas) in manufacturing while also increasing the productivity of businesses. Technology advancements that are kinder to the environment are linked to the shift to green energy and its use [34, 41], which in turn helps mitigate environmental problems and boosts the economy.

3.2. Data and empirical model

The current research made use of a secondary time series dataset for Bangladesh that stretched from 1990 to 2020. The time frame was decided upon in light of the accessibility of relevant data. World Bank [11] provided the information used for this analysis. Low-carbon economy is calculated by dividing CO_2 emissions (ton) by GDP (constant 2015 dollars). Green energy usage as a proportion of total energy blend, technological innovation as measured by patent applications (both domestic and foreign), urbanization as measured by the urban residents as a portion of the total populace, economic development as GDP per capita in constant 2015 dollars, and labor force as measured by those aged 15 and up who supply labor for the manufacture all serve as explanatory variables. The theoretical foundations for the low economy model are laid out in the following expression:

$$LCE = f(GE, TI, U, Y, L) \quad (1)$$

where LCE is the low-carbon economy, GE is the green energy, TI is the technological innovation, U is the urbanization, Y is the economic growth, and L is the labor force.

The logarithmic form of Equation (1) can also be written as:

$$LLCE_t = \tau_0 + \tau_1 LGE_t + \tau_2 LTI_t + \tau_3 LU_t + \tau_4 LY_t + \tau_5 LL_t + \varepsilon_t \quad (2)$$

where τ_0 is the intercept and ε_t is the error term. In addition, τ_1, τ_2, τ_3, τ_4, and τ_5 denote the coefficients.

3.3. Econometric strategies

The inability to predict most macroeconomic variables over time stems from the fact that they display non-stationary tendencies in time series analysis, including trends, cycles, random walks, or some amalgamation thereof. Therefore, all variables should be verified for stationarity prior to regression model estimation. One of the assumptions of the ARDL model is that all variables need to be integrated either in order I(0) or I(1); hence, testing the order of integration prior to estimating the model is also required. This study used a level- and first-difference stationarity test to ensure that all of the variables were stable. The unit root tests include the augmented Dickey–Fuller (ADF) test [52], the Dickey–Fuller generalized least squares (DF-GLS) test [53], and the Phillips–Perron (P–P) test [54]. After that, the study utilized the ARDL cointegration method proposed by Pesaran et al. [55] to determine whether the variables are cointegrated. Since both I(0) and I(1) orders of integration are supported by the ARDL method, it is a highly flexible approach [55]. Endogeneity and residual serial correlation can be avoided using this method by rearranging the lag order. The ARDL form of the model reads as follows:

$$\begin{aligned}\Delta LLCE_t &= \tau_0 + \tau_1 LLCE_{t-1} + \tau_2 LGE_{t-1} + \tau_3 LTI_{t-1} + \tau_4 LU_{t-1} \\ &+ \tau_5 LY_{t-1} + \tau_6 LL_{t-1} + \sum_{i=1}^{q} \gamma_1 \Delta LLCE_{t-i} + \sum_{i=1}^{q} \gamma_2 \Delta LGE_{t-i} \\ &+ \sum_{i=1}^{q} \gamma_3 \Delta LTI_{t-i} + \sum_{i=1}^{q} \gamma_4 \Delta LU_{t-i} + \sum_{i=1}^{q} \gamma_5 \Delta LY_{t-i} \\ &+ \sum_{i=1}^{q} \gamma_6 \Delta LL_{t-i} + \varepsilon_t\end{aligned} \quad (3)$$

where Δ are the first difference operators and q is the optimum lag length.

After determining the long-term connection between the series, this study used the following equation to calculate the short-run coefficients of the parameters:

$$\begin{aligned}\Delta LLCE_t &= \tau_0 + \tau_1 LLCE_{t-1} + \tau_2 LGE_{t-1} + \tau_3 LTI_{t-1} + \tau_4 LU_{t-1} \\ &+ \tau_5 LY_{t-1} + \tau_6 LL_{t-1} + \sum_{i=1}^{q} \gamma_1 \Delta LLCE_{t-i} + \sum_{i=1}^{q} \gamma_2 \Delta LGE_{t-i} \\ &+ \sum_{i=1}^{q} \gamma_3 \Delta LTI_{t-i} + \sum_{i=1}^{q} \gamma_4 \Delta LU_{t-i} + \sum_{i=1}^{q} \gamma_5 \Delta LY_{t-i} \\ &+ \sum_{i=1}^{q} \gamma_6 \Delta LL_{t-i} + \theta ECT_{t-1} + \varepsilon_t\end{aligned} \quad (4)$$

By solving the error correction term (ECT) in Equation (4), it is possible to determine how quickly the system returns to equilibrium following a perturbation. In addition, the symbol for the ECT coefficient is θ. ECT's estimated value is often between 0 and 1. It is feasible to balance the variance in circumstances where ECT is statistically significant and negative.

Due to the annual data and small sample size, this study decided to employ an ARDL model with a maximum lag length of 1. The best lag length for the model and ARDL model selection in this study were both determined using the Akaike information criterion. Moreover, the Jarque–Bera normality test, the Breusch–Godfrey

Lagrange multiplier (LM) test for serial correlation, the Breusch–Pagan–Godfrey heteroscedasticity test, the Ramsey reset test for model specification, and the cumulative sum of recursive residuals (CUSUM) and the cumulative sum of squares of recursive residuals were used in diagnostic and stability tests to determine the ARDL model's goodness of fit.

4. Results and Discussion

Table 1 exhibits factual data for the variables in the investigation. There is a lot of agreement between the means, medians, maximums, and minimums, indicating that all the variables follow a normal distribution. When the skewness of the data is close to zero, it is normally distributed. The data on urbanization and GDP are positively skewed, whereas the other variables are negatively skewed. The findings also demonstrated that all data followed a platykurtic distribution with less than 3. Also, the fact that Jarque–Bera has small values is indicative of a normal distribution in the dataset as a whole.

The stationarity analysis of the study's variables is shown in Table 2. Similar results can be seen across other unit root testing. All the unit root tests (ADF, P–P, and DF-GLS) revealed that the variables are now stationary at the same level as they were before the first difference was determined. The variables integrate with a first-difference method, as demonstrated by unit root investigations. Due to the nature of the factors employed in the empirical studies, it is impossible to do a false regression analysis. When comparing ARDL with cointegration, the unit root test found that the former was preferable because it ensured that no variable had a greater integration order compared to the rest.

Table 3 displays the outcomes of the ARDL bound exam. At the 5% significance level, the F-statistic beats both the critical upper and lower bound values, coming in at 10.93. This suggests that the variables are cointegrated, as the null hypothesis of no cointegration is rejected at many levels of significance. This indicates a correlation between the variables over time. This allows us to move further with the inquiry and use the ARDL cointegration method to assess the long- and short-run relationships.

Table 1
Descriptive statistics

Variables	LLCE	LGE	LTI	LU	LY	LL
Mean	−8.125	3.850	5.553	3.299	6.705	17.754
Median	−8.092	3.925	5.724	3.289	6.631	17.787
Maximum	−7.821	4.293	6.023	3.642	7.373	18.077
Minimum	−8.527	3.249	4.673	2.986	6.201	17.389
Std. Dev.	0.211	0.328	0.403	0.207	0.366	0.199
Skewness	−0.413	−0.406	−0.729	0.123	0.347	−0.188
Kurtosis	2.017	1.937	2.305	1.685	1.849	2.031
Jarque–Bera	2.127	2.313	2.396	2.312	2.332	1.395
Probability	0.345	0.315	0.408	0.315	0.312	0.498

Table 3
Result of ARDL bound test

F-bounds test		Null hypothesis: No degrees of relationship		
Test statistic	Estimate	Significance	I(0)	I(1)
F-statistic	10.929	At 10%	2.08	3.00
K	5	At 5%	2.39	3.38
		At 2.5%	2.70	3.73
		At 1%	3.06	4.15

The ARDL assessment findings, both in the long and short run, are presented in Table 4. It shows that there is a significantly negative bond between green energy and the carbon economy over both the long and short term, with a 1% intensification in green energy utilization having a 0.21% (long-run) and a 0.14% (short-run) negative consequence on the carbon economy, respectively, under the ceteris paribus assumption. These data bolster the case that a low-carbon economy in Bangladesh is stimulated by increased utilization of green energy supplies in the manufacturing activity, which in turn promotes environmental sustainability in the country. Green energy has been recognized as an effective strategy for lowering emissions and decreasing reliance on foreign fuel supplies in previous research [46, 56]. The investigation indicates that a significant boost to Bangladesh's low-carbon economy might be accomplished by increasing the usage of green energy. As a developing nation, Bangladesh is under enormous stress from the damaging consequences of climate change in recent years [12]. Accordingly, the Bangladeshi government and other stakeholders must invest in renewable power resources to maintain the nation's high ecological standards. In the context of the Bangladeshi economy, the findings corroborate those of Murshed et al. [57]. The present study finding is also justified by Pan and Dong [58], and Zeqiraj et al. [59], who reported that boosting green energy helps to achieve a low-carbon economy in China and the European Union member countries, respectively.

With the intention of realizing a low-carbon economy in Bangladesh, Table 4 also discusses the necessity of innovative green technologies. The research suggests that technological progress has a long-term adverse impression on the carbon economy of 0.18% and a short-term negative impact of 0.10%. Previous research, for instance, Wang et al. [60], Oyebanji and Kirikkaleli [41], Raihan and Tuspekova [34], Sharif et al. [46], and Xia [61] confirmed that advancements in environmentally friendly technologies are crucial to lowering carbon

Table 2
Unit root test results

Logarithmic form of the variables	ADF		DF-GLS		P–P	
	Log levels	Log first difference	Log levels	Log first difference	Log levels	Log first difference
LLCE	−1.432	−4.983***	−0.848	−3.351***	−1.436	−4.988***
LGE	−0.449	−3.699***	−0.579	−3.133***	−0.418	−3.495***
LTI	−2.115	−7.571***	−1.139	−7.702***	−2.137	−8.898***
LU	−0.506	−3.391**	−0.935	−3.196**	−1.336	−3.458***
LY	−2.606	−5.107***	−2.036	−4.173***	−2.614	−4.702***
LL	−1.687	−3.649***	−1.187	−3.709***	−1.452	−3.612***

Note: *** and ** stand for significance at 1% and 5% level.

Table 4
ARDL results on the long- and short-run effects

	Long run			Short run		
Variables	Coefficient	*t*-Statistic	*p*-value	Coefficient	*t*-Statistic	*p*-value
LGE	−0.213***	−3.376	0.006	−0.147***	−3.445	0.005
LTI	−0.181***	−3.520	0.001	−0.102***	−3.639	0.000
LU	1.143***	4.181	0.000	1.503***	4.107	0.000
LY	1.092***	4.279	0.000	1.671***	4.592	0.000
LL	0.189**	2.485	0.025	0.291**	2.652	0.014
C	24.170	1.842	0.239	–	–	–
ECT (-1)	–	–	–	−0.609***	-3.423	0.000
R^2	0.9755					
Adjusted R^2	0.9706					

Note: *** and ** stand for significance at 1% and 5% level.

output. This study's results show that a switch to a low-carbon economy in Bangladesh is possible with further development of green innovation. The present study finding is justified by Zhu et al. [62] and Zeqiraj et al. [59], who reported that enhancing green technological innovation facilitates to attain low-carbon economy in China and the European Union member countries.

The urbanization coefficient, however, demonstrates that urbanization has substantial long- and short-term positive possessions on the carbon economy. Increasing urbanization by 1% has the potential to raise CO_2 emissions by 1.14% (long run) and 1.50% (short run) if all other influences persist constant. As a result, it demonstrates conclusively that urbanization has a negative influence on ecological conditions since it raises emissions and increases the abuse of ecological assets and the burden on urban sewage and sanitation systems [49]. The result of the positive link between urbanization and carbon economy is justified by Sun et al. [63], Alola et al. [64], Erdoğan et al. [65], Verbič et al. [66], Chen et al. [67], and Raihan et al. [12], who reported that snowballing urbanization causes increased CO_2 emissions in MENA region, OECD countries, African countries, Europe, BRICS economies, and Bangladesh, respectively. The outcomes of this analysis propose that limited urbanization is a critical factor in helping Bangladesh achieve a low-carbon economy.

The economic progression index is really encouraging. These data suggest that Bangladesh's burgeoning economy has a salutary consequence on the global carbon market. In the short run, a 1% rise in GDP per capita will boost the carbon economy by 1.67%, and in the long run, it will increase the economy by 1.09%. This is due to the fact that fossil fuels account for 74% of overall energy consumption in the Bangladeshi economy, whereas just 30% of energy consumption comes from green sources [11]. Guo et al. [68] followed by Pan and Dong [58] found that using more fossil fuels in production raises the carbon economy. Ahmad et al. [69] argued that the EKC hypothesis is correct because short-term economic growth is more important than long-term growth. Since the short-run coefficient of economic development (1.67) is larger than the long-run coefficient (1.09), the analysis outcomes confirmed the presence of EKC in Bangladesh. A similar type of relationship between economic growth and carbon economy to validate the EKC hypothesis has been reported by a number of studies in the literature, including those by Sultana et al. [70] in Bangladesh, Suki et al. [71] in Malaysia, Ahmad et al. [69] in Pakistan, Chang et al. [72] in China, Genç et al. [73] in Turkey, Cheikh et al. [74] in MENA region, Verbič et al. [66] in Europe, and Pata et al. [75] in ASEAN countries.

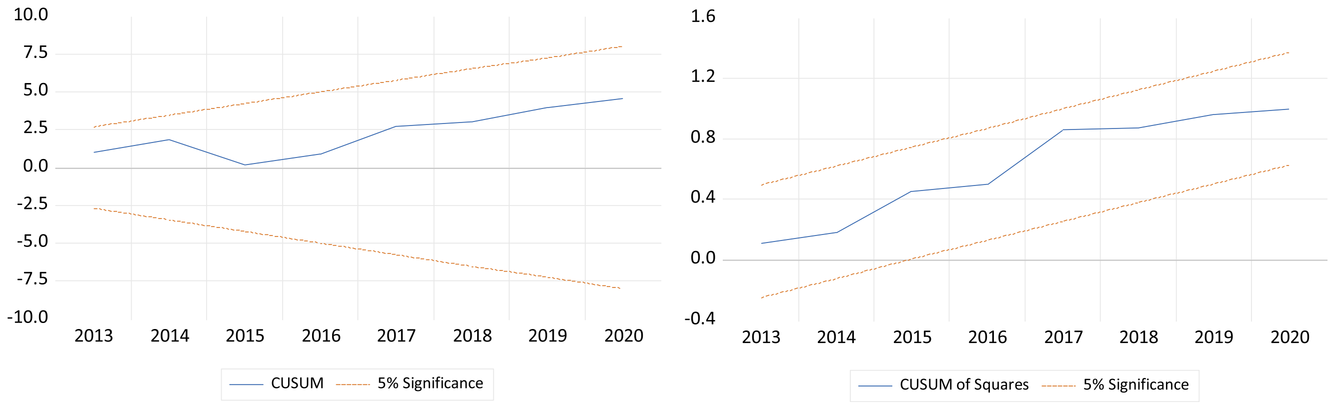
In addition, the study examined the workforce's part in explaining Bangladesh's low-carbon economy and uncovered some fascinating observations. The analysis concluded that there is a positive interaction between the nation's labor force and carbon economy at a 5% level of significance. A significantly positive long-run and short-run labor force coefficient indicates that a 1% improve in the labor supply benefits the carbon economy by 0.19% (long run) and 0.29% (short run), respectively. These findings are consistent with prior research, for instance, Hao et al. [76], Lasisi et al. [77], and Samargandi and Sohag [24].

Both theory and practice are in agreement with the assessment's predicted coefficients. With an R^2 of 0.9755 and an adjusted R^2 of 0.9706, the evaluated regression model is a good fit for the dataset. If that is the case, then shifts in the independent factors might give an explanation for around 97% of the adaptation in the reliant variable. Furthermore, the ECT coefficient is 0.61, which is negative at the 1% level of significance. This indicates that any imbalances that exist in the near term will be corrected in the long run by 61%. In addition, the ARDL analysis diagnostic tests are listed in Table 5. Among them are checks for model stability, multicollinearity, and heteroscedasticity. The absence of heteroscedasticity and multicollinearity was confirmed by all diagnostic tests. Parameter stability is depicted in Figure 1 using the CUSUM and CUSUM squared graphs.

Table 5
The outcome of diagnostic tests

Diagnostic tests	Coefficient	*p*-value	Decision
Jarque–Bera test	1.295386	0.8456	Residuals are normally distributed
Breusch–Godfrey LM test	1.321315	0.1176	No serial correlation exits
Breusch–Pagan–Godfrey test	0.702631	0.7502	No heteroscedasticity exists
Ramsey RESET test	0.171065	0.4042	The model is properly specified

Figure 1
Results of CUSUM and CUSUM squared analysis



5. Conclusion and Policy Implications

Energy demand in recent years has increased in Bangladesh because of the country's rapid urbanization, industrialization, and population growth, all of which have created new ecological difficulties. Since the country is suffering historic losses because of climate change's negative effects, it is important to pinpoint the macroeconomic elements that can help alleviate the country's mounting environmental problems. In light of this, the current research created a series to use carbon emissions per GDP as a stand-in for the economic condition and investigated the role of renewable power, innovation in technology, and growth in the economy, urbanization, and human labor in Bangladesh's pursuit of a low-carbon economy. The study used data from 1990 to 2020 applying the ARDL technique to draw some intriguing conclusions. The empirical outcomes exposed that a 1% increase in urbanization, economic growth, and labor force would lead to 1.14%, 1.09%, and 0.19% upsurge in carbon economy in the long run, while 1.67%, 1.50%, and 0.29% increase in the short run, respectively. However, the results indicated that a 1% boost in green energy utilization and technology innovation would result in a 0.21% and 0.18% decline in the carbon economy in the long run, whereas 0.15% and 0.10% drop in the short run, respectively. The outcomes of the investigation showed that green energy and technological innovation help to create a low-carbon economy and slow down ecological deprivation in Bangladesh. While expanding the economy's carbon intensity leads to a carbon economy at first, it ultimately drives the country to a low-carbon economy. These expansionary economic effects proved the validity of the EKC concept for Bangladesh. In addition, environmental quality is decreasing as a result of increased urbanization, which drives the country toward a carbon economy. Worker numbers also influence the country's carbon intensity, which in turn drives the development of a carbon-based economy. This report provides policymakers and environmentalists with several policy proposals based on empirical findings.

The administration of Bangladesh could advance a carbon evaluating mechanism in the territory to discourage CO_2-stimulating activities, promote a low-carbon economy, and boost economic competence by introducing more cost-effective manufacturing methods. It is essential that the first scope of this carbon pricing instrument includes industrial and fossil energy production, as these are the primary emitters in the nation liable for growing the carbon economy. Furthermore, it is recommended that urbanization in Bangladesh be carried out sustainably by promoting greenhouse schemes and green transport in urban zones, as well as by announcing deliberate cities in rural parts, as urbanization is found to be linked with the extension of the carbon economy and is seen as the foremost reason of energy deficit. In addition, the administration would prioritize fiscal decentralization to promote more environmentally friendly patterns of consumption and production, especially in the country's major cities.

Since the study found that technological innovation is the furthermost imperative aspect in safeguarding environmental sustainability over the long term, the government of Bangladesh should prioritize eco-innovative approaches to the manufacture of goods and services by investing heavily in R&D. Finally, the central administration might prioritize green growth over brown growth and green energy consumption in order to take care of the expanding carbon economy, as the substitution of renewable energy resources for fossil fuels in the manufacturing procedure not only changes the makeup of the manufacturing segment but also has the possible revolutionary impact in the push for a low-carbon economy. Since green economic development is widely regarded as a crucial factor in determining environmental sustainability, Bangladesh should prioritize this strategy to achieve not only its NDC goals but also the overarching SDGs. But green energy usage in manufacturing, together with green supply chain technologies and innovations, can accomplish the goal of green growth.

There are two caveats to this study that could be explored further. For starters, this research focuses on Bangladesh, which may be of more interest to other emerging nations. Results may be more generally relevant in the future if additional developing nations are analyzed or if the sample size is increased. Second, the present study applied econometric methods by using time series data for only 31 years (1990–2020) because of the data unavailability regarding green energy and technological innovation beyond the study period. Moreover, the study employed macro data and scrutiny to assess the significance of green energy, technical advancement, and urbanization in understanding Bangladesh's low-carbon economy. Future research with enterprise-level data could take this kind of study down to the debate and analysis of the micro-level.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by the author.

Conflicts of Interest

The author declares that he has no conflicts of interest to this work.

Data Availability Statement

Data available on request from the corresponding author upon reasonable request.

Author Contribution Statement

Asif Raihan: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization.

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