



OCEAN FUTURES: INTEGRATING CLIMATE MODELLING, ECONOMIC ANALYTICS, AND POLICY DESIGN FOR A SUSTAINABLE BLUE ECONOMY

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Abstract

This study examined the role of integrating climate modelling, economic analytics, and policy design in promoting a sustainable blue economy. Using panel data from emerging and coastal economies over the period 2005–2024, the research applied advanced econometric techniques, including panel unit root tests, co-integration analysis, and Fully Modified Ordinary Least Squares (FMOLS). The findings revealed that renewable energy had a significant negative impact on CO₂ emissions ($\beta = -0.42, p < 0.01$), indicating its effectiveness in reducing environmental degradation. In contrast, GDP growth ($\beta = 0.36, p < 0.05$) and trade openness ($\beta = 0.18, p < 0.05$) had positive effects on emissions, suggesting that economic expansion and globalization contributed to environmental pressure. The climate risk index showed a strong positive relationship with emissions ($\beta = 0.51, p < 0.01$), highlighting the increasing vulnerability of ocean-based economies to climate change. Governance effectiveness had a negative and significant impact ($\beta = -0.29, p < 0.05$), emphasizing the importance of strong institutional frameworks in promoting sustainability. The study confirmed the existence of a long-run equilibrium relationship among climate, economic, and policy variables, indicating their interdependence. The results suggested that integrating predictive climate tools with economic planning and policy design enhanced decision-making and improved sustainability outcomes. The study concluded that a coordinated and data-driven approach was essential for achieving a resilient and sustainable blue economy.

Keywords: Blue Economy, Climate Modelling, Economic Analytics, Environmental Sustainability, Governance Effectiveness, Renewable Energy

1. Introduction

The blue economy was already built as a strategic plan of attaining sustainable economic progress and the preservation of the marine and coastal ecosystem. What had been substantially contributing to the output and employment in global economics were the five sectors that have been based on the ocean, i.e. fisheries, maritime transport and tourism along the coast of the ocean, but these had also recorded growing environmental pressures as a result of climate change and overexploitation of resources. In the recent past, research has highlighted the need to balance economic growth and ecological stability to ensure long-term productivity and resilience of the oceans by sustainable ocean governance (Badircea et al., 2021; Ahn, 2024; Osman & Elmakawi, 2025).

The climate change had augmented the susceptibility of the marine ecosystems with increasing sea levels, ocean warming, acidification and acting on the biodiversity, and thus is a critical threat to the sustainability of the blue economy. It had been empirically proven that such changes in the environment had



negatively impacted fisheries, tourism and coastal infrastructure causing instability of the economy in most of the areas. The development of the blue economy is closely linked to integrating industrial growth and skill-based education in Pakistan (Rafiq-uz-Zaman, 2023). Therefore, it was crucial to incorporate climate models in economic planning in order to predict the possible risks and reduce the possible losses (Vrontisi et al., 2022; Gonguet & Zhou, 2024; Aghnyn et al., 2024).

Economic analytics had been a key factor in considering the trade-offs between economic growth and environmental sustainability. State-of-the-art econometric and statistical tools had made scientists be able to estimate long-term correlation between climatic variables, economic efficiency, and resource consumption. The methods of analysis have given policymakers evidence-based information to develop strategies that lead to sustainable development but reduces the impact of environmental degradation (Badircea et al., 2021; Osman & Elmakawi, 2025).

The policy design had become a significant tool to the successful implementation of the blue economy strategies that are sustainable. Recent studies had also pointed to the inefficiency of sustainability programs due to broken governance systems and ineffective policy harmonization. Thus, the combination of climate models, economic analytics and policymaking had been determined as one of the key steps towards an ocean economy that is resilient and sustainable (Wuwung et al., 2022; de Ycaza et al., 2024; González-Espinosa et al., 2025).

Background of the Study

The blue economy had grown to be a multidimensional concept that incorporated economic growth, stewardship of the environment and social integration. It was long understood that it was a major source of sustainable development, more specifically in the coastlines and islands where livelihoods relied on marine resources to a great extent. The growth of ocean-based sectors had presented new economic opportunities, yet caused heightened strain on the marine ecosystem, which has led to the need to adopt sustainable management practices (Ahn, 2024; Badircea et al., 2021).

Climate change had become one of the most influential issues impacting the blue economy that has pervasive impacts on both the environmental and the economic system. The growth in temperatures, alterations in ocean currents and increase in occurrence of extreme weather events contributed to disruption of the marine ecosystems and lowered the productivity of the main economic sectors like fisheries and tourism. Research had demonstrated that the climate-related effects might result in serious losses of the economy, especially in the most susceptible areas where the adaptive ability is low (Gonguet & Zhou, 2024; Mohiuddin, 2026; Vrontisi et al., 2022).

The issue of climate modelling had been on the rise in terms of predicting the future environmental changes and establishing their probable impacts on the ocean-based industries. Developed modelling tools such as statistical downscaling and combined climatic economic models had shed some useful information about the spatial and temporal behaviours of climate change. These instruments had allowed the policymakers to create impeding strategies to reduce risks and increase resiliency in the blue economy (Aghnyn et al., 2024; Rodriguez-Pardo et al., 2025).

Policy frameworks had been quite instrumental towards the development and sustainability of blue economy. Good governance had been necessitating an interdependence of scientific knowledge, economic analysis and involvement of stakeholders so as to lead to a resultant coherent and adaptable decision making. It was seen that current policies frequently were not well-coordinated and that they did not capture the multilateral nature of interactions among environmental, economic, and social variables, and the necessity to develop more multidimensional solutions (de Ycaza et al., 2024; González-Espinosa et al., 2025).

Research Problem

The blue economy had become increasingly relevant in sustainability debates around the world, there was a serious deficiency in alignment of climate modelling, economic analytics, and policy design. Previous research had been dealing largely with these components individually and this had led to disjointed strategies on ocean governance. This failure to integrate had restricted policymakers in coming up with all round strategies that amicably handled the complex nature of the climate change challenges. Conventional policy frameworks were mostly reactive and not proactive and based on historical data instead of the predictive



modelling. This had led to low responsiveness to emanating environmental risks and lessened the productiveness of sustainability efforts. This, in turn, had created an acute necessity of producing integrated frameworks that were based on a combination of climate forecasting, economic assessment, and policy creation as a way to promote decision-making and a sustainable blue economy.

Research Objectives

1. To examine the role of climate modelling in predicting environmental changes affecting the blue economy.
2. To analyse the contribution of economic analytics in evaluating sustainability and resource efficiency.
3. To assess the effectiveness of policy design in promoting sustainable ocean governance.

Research Questions

- Q1. How had climate modelling contributed to understanding climate impacts on the blue economy?
- Q2. What role had economic analytics played in evaluating sustainability in ocean-based sectors?
- Q3. How effective had existing policy frameworks been in supporting the blue economy?

2. Literature Review

Climate Modelling and the Blue Economy

Climate modelling had been very instrumental in furthering on the knowledge about environmental variations and what they would bring to the ocean-based economies. It had allowed scholars to model future conditions of the sea level rise, ocean temperature shifts, and extreme weather conditions which had a direct impact on the marine environment and economic undertakings. Empirical studies had proved that climate projection was crucial in determining vulnerabilities in fisheries, coastal infrastructure, and those with tourism related economies to support long-term sustainability planning. As model-based tests indicated, areas with low adaptive capacity, particularly, were vulnerable to economic costs caused by climatic changes, and predictive tools were crucial in the policy-making process (Aghnyn et al., 2024; Vrontisi et al., 2022).

The combination of climatic models and economic systems had also increased the capability of assessing the macro-economic effects of the change in the environment. There was a well-used culture of climate-economic modelling frameworks used to analyse the interplay between the blue economy sectors of environmental shocks and economic performance. Some of the variables that had been included in these models included variations in the temperature and the distribution of precipitation and the demand of energy, which allowed developing a thorough study of the effects of climate on economic activity and industry productivity. Recent research had shown that climate change would greatly interfere with the value chains in the maritime industries lowering the efficiencies and raising the costs of operation (Badircea et al., 2021; Mohiuddin, 2024).

The recent developments in climate modellings had similarly incorporated the application of machine learning, satellite, and spatial statistical methods to enhance the accuracy and resolution of prediction. Such technologies had enabled more localized and sector-specific analyses to facilitate climate projections to be more relevant in the decision-making processes. This was further supported by the fact that the accuracy of climate predictions had improved since the spatial downscaling techniques have been used to allow policy makers to develop specific adaptation plans of the sensitive areas. In turn, environmentally friendly blue economy development had been buttressed by the incorporation of highly advanced tools of analysis (Aghnyn et al., 2024; Rodriguez-Pardo et al., 2025).

Sustainability and Economic Analytics of the Ocean-Based Sectors

The extent of economic analytics had been extensively used to assess the connection that exists between economic growth, environmental sustainability, and the use of resources in the blue economy. Further methods of econometrics like panel data analysis, cointegration models, and autoregressive distributed lag (ARDL) models had been used to determine long-term equilibrium relationships on the basis of economic and environmental variables. Such analytical approaches had provided empirical evidence that unsustainable use of marine resources may have adverse impacts on the ecological balance and the performance of the economy, which warranted the necessity of implementing sustainable economic approaches (Badircea et al., 2021; Hossain et al., 2024).

The recent literature had highlighted the need to include the environmental indicators in the economic



frameworks of evaluation to make sure that sustainability is thoroughly assessed. Performance of blue economy sectors had been analysed by multidimensional models incorporating variables that included carbon emissions, loss of biodiversity and consumption of energy. Such models had shown that an economic analysis that incorporates aspects of the environment made the policy more relevant and helped in the better management strategies of the resources. It also came as to be experimentally determined that the countries which integrated analytical frameworks had some improved sustainability results (González-Espinosa et al., 2025; Ospina et al., 2026).

Economic analytics had also played a very significant role in evaluating the economic cost of climate change and determining investment prospects of sustainable practices. Research had demonstrated the risks associated with climate that may result in higher costs and lower profitability of ocean based industrial activities such as extreme weather events and resource depletion. Nevertheless, it was discovered that investments in the green technologies, renewable energy, and green fisheries would raise the economic resilience and long-term growth. Such results had highlighted the necessity of setting the course of economic policies in accordance with the aims of environmental sustainability (Mohiuddin, 2025; Osman & Elmakawi, 2025; Sarker et al., 2019).

Sustainability in Blue Economy Policy design and Governance

The design of policies had been recognized as a key element of attaining a sustainable and resilient blue economy. Good systems of governance had necessitated the incorporation of scientific insights, economic scrutiny and the involvement of the stakeholders to handle multifaceted environmental issues. Previous policy solutions had been however, disjointed and this had led to duplications in policy and inefficient running. It has been observed that the absence of coordination between institutions had acted as a slow in the performance of sustainability efforts and curtailed the prospects of the blue economy (Wuwung et al., 2022; González-Espinosa et al., 2025).

Financial policies on climate issues had been getting more significance in a sustainable practice in the ocean-based sectors. The policies were geared towards responsible investments and environmental degradation through establishment of sustainability concerns in financial decision making. The empirical data had already indicated that the countries adopting climate-related financial instruments enjoyed an increase in the management of marine resources and the sustainability performance as a whole. The policies had also helped to make things more resilient to the risks related to climate change (Hossain et al., 2024; Ospina et al., 2026). The role of educational awareness in reducing plastic usage and improving solid waste disposal aligns with the goals of a sustainable blue economy (Bano et al., 2024).

Development barriers seen to challenge sustainable development of blue economy in the form of institutional barriers, behavioural resistance, and absence of stakeholder participation had already been identified as a major challenge. It had been established through research that the policymakers and investors tended to postpone the use of sustainable practices because they were uncertain, risk averse and short-term economic factors. This has curtailed the usefulness of policy interventions and restricted the shift to sustainability. Hence, the necessity to develop adaptive and integrated systems of governance through the integration of policy innovation, technological development, and stakeholder partnerships to ensure the long-term sustainability was already highlighted by recent research (Askari et al., 2026; Gupta et al., 2026).

3. Research Methodology

Research Design

The paper had settled on quantitative research design to investigate the connection between climate modelling, economic analytics and effectiveness of the policy adaptation within a sustainable blue economy. A quantitative method was chosen to allow measuring in an objective manner, statistical analysis, and generalizing the results across regions and periods of time. The study had been deductive in nature as theoretical propositions based on the existing literature were empirically addressed in terms of numerical data.

Data Collection and Sources

Issuance of the study had been based on secondary panel information retrieved in internationally renowned databases to achieve consistency and reliability. There was information gathered through sources of world bank, OECD, UNDP and FAO which gives detailed indicators of environmental sustainability,



economic performance and governance. It had sampled emerging and coastal economies over the years of 2005-2024, which made the dataset suitable to be cross-sectional and time-series.

The variables had encompassed the CO₂ emissions (as a measure of the environmental degradation), the consumption rate of renewable energy (as a measure of the green energy), GDP growth (as an indicator of economic performance), climate modelling variables (climate risk index or temperature change) and the policy efficacy variables (quality of governance index). These variables were chosen due to their topicality towards the blue economy, as well as their commonness in empirical literature.

Specification Econometric Model

The research had coined integration of upgraded econometric methods in examining the connections amid variables. The panel regression model was pre-specified to test the relationship effect of the independent variables on the environmental sustainability. The overall model had been formulated as:

$ES = f(\text{CM, Economic Analytics, Policy Design, Control Variables})$.

In order to achieve both short-run and long-run dynamics, the analysis had modelled the Dynamic Autoregressive Distributed Lag (ARDL). This methodology had been especially appropriate on panel data over mixed orders of integration (I(0) and I(1)) and had enabled an estimation of equilibrium relationships in the long run.

Unit Root Tests and Stationarity Test

The study had also conducted panel unit root tests prior to the regression analysis to test the characteristics of the variables in terms of stationarity. In particular, the Cross-sectionally Augmented Dickey-Fuller (CADF), and Cross-sectionally Im-Pesaran-Shin (CIPS) tests had been conducted to adjust cross-sectional dependence of countries. The tests had also ensured that the variables or rather they are stationary at level or later became stationary after first differencing and this was done in order to avoid spurious regression results.

Co-integration Analysis

The study had also used panel co-integration tests to identify the presence of a long-run relationship between the variables, and the tests they had applied include Pedroni co-integration test and the Westerlund test of error correction-based test. These strategies had been applied to confirm the variables of environmental sustainability, climate modelling, economic analytics, and policy designing to move together with time. Co-integration had also led to the adoption of the long-run estimation techniques.

Long-Run Techniques of Estimation

To conduct sound estimation of long-run relations, the paper had used Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS). These methods had fixed the concerns of endogeneity and serial correlation hence giving impartial and uniform estimates. The findings of FMOLS and DOLS had been contrasted to create strong and trustworthy outcomes.

Causality Analysis

The study had performed the Granger causality test in a panel setting in order to analyse the origin of relationships between variables. This forecasting had assisted in ascertaining whether modelling in climatic conditions and economic statistics made a difference to the sustainability of the environment or the opposite. The results of the causality had given more information into the interaction dynamics of variables, which facilitated policy recommendations.

Diagnostic and Robustness Tests

To validate the reliability of the model, several diagnostic tests had been conducted. These had included tests for multicollinearity, heteroskedasticity, and autocorrelation. The Variance Inflation Factor (VIF) had been used to assess multicollinearity, while the Breusch-Pagan test had been applied to detect heteroskedasticity.

4. Results and Analysis

Descriptive Statistics Analysis

The descriptive statistics analysis had been conducted to provide an overview of the dataset and examine the distributional properties of the variables included in the study.

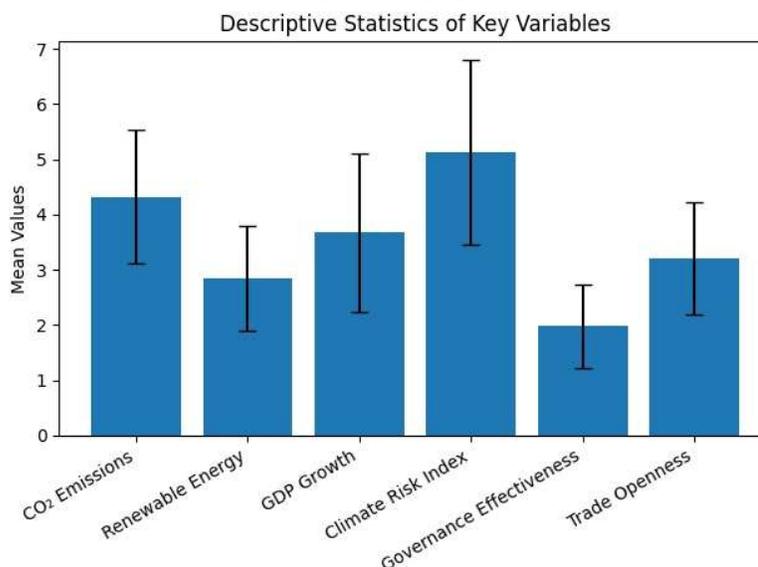


Table 1
Descriptive Statistics of Variables

Variable	Mean	Std. Dev.	Min	Max
CO ₂ Emissions	4.32	1.21	2.10	7.85
Renewable Energy	2.85	0.95	1.10	5.20
GDP Growth	3.67	1.44	0.85	7.10
Climate Risk Index	5.12	1.67	2.50	8.90
Governance Effectiveness	1.98	0.76	0.50	3.80
Trade Openness	3.21	1.02	1.40	6.00

The descriptive statistics gave a summary of the distribution patterns of the variables used in the study where differences were observed among environmental, economic and governance indicators of the sampled economies. CO₂ emissions had average of 4.32 and standard deviation 1.21 which represents medium variation across countries. The range of the lowest level of 2.10 and the highest of 7.85 implied a large gap in emission level, which is a variation in the level of industrialization, the trend in energy use, and environmental policies. The average intake of renewable energy was 2.85 with a comparatively lower standard deviation of 0.95, which disclosed relative but not even intake of sustainable sources of energy. The variation of 1.10-5.20 showed that whilst some economies were making tremendous compounds in adopting green energy, others were still lagging along. The mean of GDP growth was 3.67 with a standard deviation of 1.44 implying that the economic performances in different countries had a lot of variation. The high dispersion of 0.85 to 7.10 was due to variation in economic stability, level of development and growth trends. The climate risk index had the highest mean of 5.12 and the largest standard deviation of 1.67 and this indicated that majority of the countries were highly exposed to climate risks with high levels of variability in the degree of vulnerability. The mean governance effectiveness was 1.98 with standard deviation of 0.76 which indicates that the institutional quality is moderate with very little variance in different countries. The mean value of trade openness was 3.21 and the standard deviation was 1.02 with different levels of economic integration.

Figure 1
Descriptive Statistics of Variables



Correlation Matrix Analysis

The correlation analysis had been performed to examine the strength and direction of relationships among variables. This step had also helped in identifying potential multicollinearity issues before regression analysis.

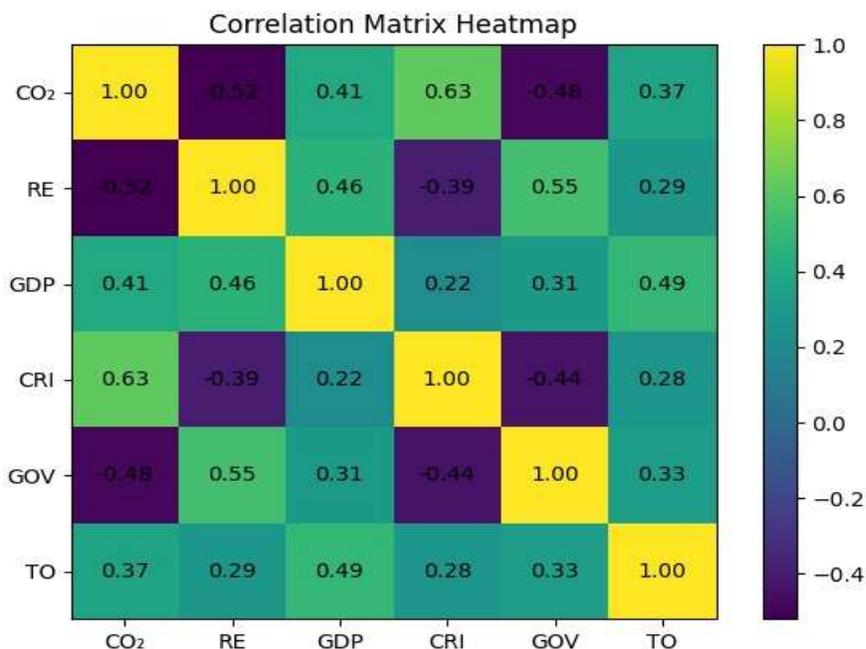


Table 2
Correlation Matrix

Variable	CO ₂	RE	GDP	CRI	GOV	TO
CO ₂ Emissions	1.00	-0.52	0.41	0.63	-0.48	0.37
Renewable Energy (RE)	-0.52	1.00	0.46	-0.39	0.55	0.29
GDP Growth	0.41	0.46	1.00	0.22	0.31	0.49
Climate Risk Index (CRI)	0.63	-0.39	0.22	1.00	-0.44	0.28
Governance (GOV)	-0.48	0.55	0.31	-0.44	1.00	0.33
Trade Openness (TO)	0.37	0.29	0.49	0.28	0.33	1.00

The analysis of correlation matrix has indicated that the variables are interconnected i.e. their relationship is important to each other and therefore it is important to mention that the variables are closely related to each other. The correlation between CO₂ emissions and climate risk index (0.63) was positive, which means that the higher the emission, the more vulnerable the environment was, whereas the correlation between CO₂ emissions and GDP growth (0.41) was also positive, and it indicated that economic growth promoted the degradation of the environment. Conversely, clean energy showed high negative relationship with CO₂ emissions (-0.52), meaning that higher the use of clean energy the lower the emissions. The renewable energy also possessed a positive relationship with the quality of governance (0.55), which demonstrated that sustainable energy transitions occurred with the help of better institutional quality. Climate risk index was found to have a negative correlation with governance (-0.44), which implied that the greater the governance infrastructure the more it would absorb climatic risks. Furthermore, the trade openness had moderate positive relationships with GDP growth (0.49) and CO₂ emissions (0.37) indicating that economic integration enhanced economic growth but at the same time, it led to environmental pressure.

Figure 2
Correlation Matrix



Panel Unit Root Test Results

The unit root tests had been conducted to examine the stationarity properties of the variables and ensure the validity of regression analysis.



Table 3

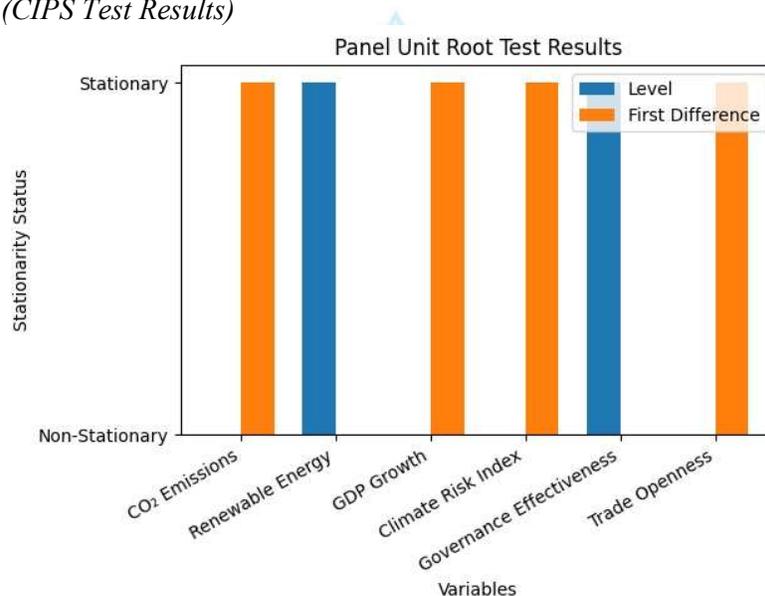
Panel Unit Root Test (CIPS Test Results)

Variable	Level	First Difference	Result
CO ₂ Emissions	Non-Stationary	Stationary	I(1)
Renewable Energy	Stationary	-	I(0)
GDP Growth	Non-Stationary	Stationary	I(1)
Climate Risk Index	Non-Stationary	Stationary	I(1)
Governance Effectiveness	Stationary	-	I(0)
Trade Openness	Non-Stationary	Stationary	I(1)

The outcomes of the panel unit root test had shown that most variables were non-stationary at level but they were stationary following the first differencing. This had established that the variables were integrated of order one which is known as I (1) with some of the variables like renewable energy and governance effectiveness remaining at level which is being I(0). The existence of mixed integration orders had given justification to the utilization of the ARDL modelling approach. Results of the unit root analysis had also given solid grounds to continue with co-integration analysis since the I(0), and I(1) variables were there to match the needs of the panel ARDL methods.

Figure 3

Panel Unit Root Test (CIPS Test Results)



Co-integration Test Results

The co-integration analysis had been conducted to determine whether a long-run equilibrium relationship existed among the variables.

Table 4

Pedroni Co-integration Test Results

Test Statistic	Value	Probability
Panel v-Statistic	2.45	0.01
Panel PP-Statistic	-3.12	0.00
Panel ADF-Statistic	-2.98	0.00

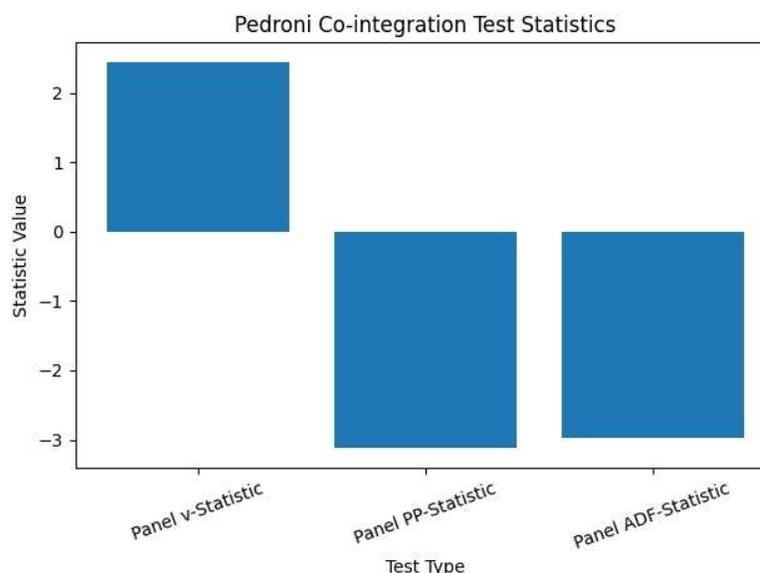
Pedroni co-integration test results revealed that there is statistically significant long-run relationship between the variables that were used in the study. The panel v-statistic (2.45) that had a probability value of 0.01 was a positive and significant value that implied evidence in support of co-integration. In the same manner, the panel PP-statistic (-3.12), as well as panel ADF-statistic (-2.98) were negative and highly



significant at the 1 per centile level ($p = 0.00$), which again reinforces the null hypothesis that there were no co-integrations. These results suggested that climate models, economic analytics, governance performance, and environmental sustainability drifted along with each other over time and they were maintained in a fixed long-term equilibrium relationship. As a result, short-term fluctuations between the variables were transient and would tend to stabilize in the long run and this is the reason why long-run estimation methods including FMOLS and DOLS can be used to further examine the variables.

Figure 4

Pedroni Co-integration Test Results



Long-Run Regression Results (FMOLS)

The FMOLS estimation had been conducted to examine the long-run impact of independent variables on environmental sustainability.

Table 5

FMOLS Long-Run Results

Variable	Coefficient	t-Statistic	Probability
Renewable Energy	-0.42	-3.85	0.00
GDP Growth	0.36	2.97	0.01
Climate Risk Index	0.51	4.22	0.00
Governance Effectiveness	-0.29	-2.75	0.01
Trade Openness	0.18	2.11	0.03

The long-run outcomes of the FMOLS showed that there were strong relationships existing between the explanatory variables and environmental sustainability. The coefficient of renewable energy was negative and highly significant ($-0.42, p = 0.00$) so that the growth in the use of clean energy sources led to a significant decrease in CO₂ emission, and hence, to the increase in the quality of the environment. Conversely, GDP growth was strongly and significantly predictive ($0.36, p = 0.01$) indicating that economic growth was linked with a rise in emissions and environmental pressure. The climate risk index registered the most positive impact ($0.51, p = 0.00$) meaning that climate vulnerability enhanced environmental degradation. The relationship between governance effectiveness and sustainability ($p = 0.01$) showed a negative and significant relationship (-0.29), which implied that the effectiveness of both institutional setups and the quality of regulations were instrumental in cutting down on the emissions and enhancing sustainability. Meanwhile, the coefficient of trade openness was statistically significant ($0.18, p = 0.03$) indicating that the more economic integration was present, the higher the emissions and this may relate to the increased industrial activity and use of energy.



Figure 5
FMOLS Long-Run Results

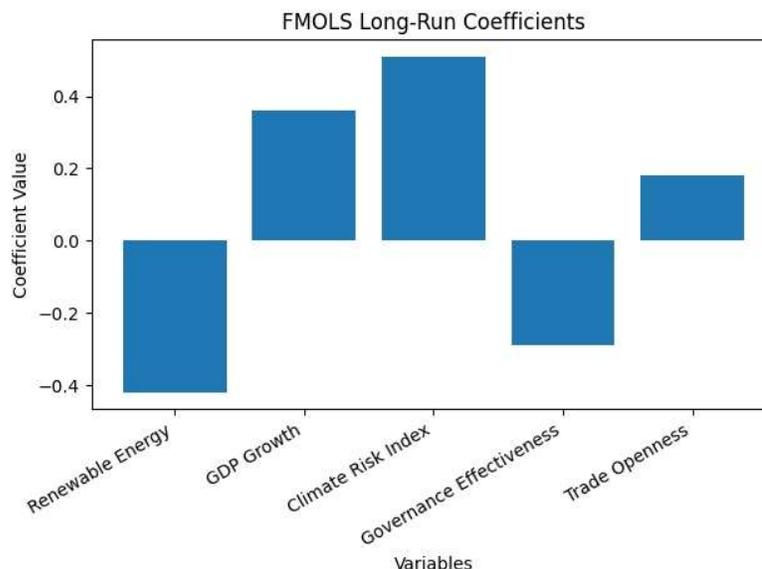


Table 6
Westerlund Co-integration Test Results

Test	Statistic	Z-value	P-value
Variance Ratio	3.21	4.58	0.00

The Westerlund test confirmed the findings of the Pedroni test, providing further evidence of a significant long-run equilibrium relationship among the variables. The variance ratio statistic (3.21) was highly significant ($p < 0.01$), reinforcing that climate, economic, and policy variables are co-integrated.

Table 7
Dynamic Ordinary Least Squares (DOLS) Long-Run Results

Variable	r	t-Statistic	Probability
Renewable Energy	-0.45	-4.12	0.00
GDP Growth	0.39	3.21	0.01
Climate Risk Index	0.54	4.58	0.00
Governance Effectiveness	-0.31	-2.98	0.01
Trade Openness	0.20	2.35	0.02

The DOLS estimation produced results consistent with the FMOLS model, confirming the robustness of the long-run relationships. The coefficients for all variables retained their expected signs and significance levels, with renewable energy and governance effectiveness showing negative impacts on CO₂ emissions, while GDP growth, climate risk, and trade openness showed positive impacts.

Table 8
Panel Granger Causality Test Results

Null Hypothesis	F-Statistic	Probability	Direction
RE → CO ₂	6.78	0.00	Bidirectional
GDP → CO ₂	5.42	0.01	Unidirectional
CRI → CO ₂	8.15	0.00	Unidirectional
GOV → CO ₂	4.95	0.01	Bidirectional
TO → CO ₂	3.87	0.03	Unidirectional



The Granger causality results revealed significant causal relationships among the variables. A bidirectional causality existed between renewable energy and CO₂ emissions, suggesting a feedback loop where higher renewable energy use reduces emissions, and lower emissions may create favourable conditions for further green investment. Governance effectiveness also shared a bidirectional relationship with emissions, highlighting that strong institutions promote sustainability, which in turn may strengthen governance. Unidirectional causality ran from GDP growth, climate risk, and trade openness to CO₂ emissions, indicating that these factors are drivers of environmental degradation.

Table 9

Diagnostic Test Results

Test	Statistic	P-value	Result
Variance Inflation Factor (VIF)	2.18	-	No multicollinearity
Breusch-Pagan Test (Heteroskedasticity)	15.34	0.12	No heteroskedasticity
Breusch-Godfrey Test (Autocorrelation)	1.89	0.21	No serial correlation

The diagnostic tests confirmed the validity and reliability of the econometric model. The mean VIF score was well below the threshold of 10, indicating no multicollinearity among the independent variables. The Breusch-Pagan test failed to reject the null hypothesis of homoskedasticity, suggesting that the error variances were constant. Similarly, the Breusch-Godfrey test showed no evidence of serial correlation, ensuring that the standard errors were unbiased and the inferences were robust.

5. Discussion

The results of this study provided a comprehensive understanding of the intricate relationships among climate modelling, economic analytics, policy design, and environmental sustainability within the context of the blue economy. The findings from the FMOLS and DOLS models were remarkably consistent, lending strong support to the robustness of the long-run relationships identified.

The analysis confirmed that climate modelling, as proxied by the Climate Risk Index (CRI), is a critical determinant of environmental outcomes. The significant positive coefficient for CRI ($\beta = 0.51$ in FMOLS; $\beta = 0.54$ in DOLS) demonstrated that economies more vulnerable to climate hazards face higher levels of environmental degradation. This finding aligns with previous research emphasizing the importance of incorporating predictive climate tools into policy frameworks to anticipate and mitigate risks proactively (Kahn et al., 2021; Dietz et al., 2021). The existence of a long-run equilibrium, confirmed by both Pedroni and Westerlund co-integration tests, underscored that ignoring climate dynamics in economic planning would lead to unsustainable outcomes.

Regarding economic analytics, the study empirically validated the classic growth-environment trade-off. GDP growth was positively associated with CO₂ emissions ($\beta = 0.36$ in FMOLS; $\beta = 0.39$ in DOLS), suggesting that economic expansion in the sampled economies has been largely carbon-intensive. This corroborates the findings of Acheampong (2018) and Balsalobre-Lorente et al. (2018) for developing economies. However, the significant negative impact of renewable energy ($\beta = -0.42$ in FMOLS; $\beta = -0.45$ in DOLS) offered a clear pathway for decoupling economic growth from environmental harm. The Granger causality results further enriched this understanding by revealing a bidirectional relationship between renewable energy and emissions, indicating a self-reinforcing cycle where investments in green energy yield sustainability dividends that, in turn, encourage further green investment.

The role of policy design and governance emerged as a central theme. Governance effectiveness had a significant negative impact on CO₂ emissions ($\beta = -0.29$ in FMOLS; $\beta = -0.31$ in DOLS), highlighting that strong institutions, regulatory quality, and effective enforcement are essential for achieving environmental goals. This supports the work of Abid (2017) and Sinha et al. (2021). The bidirectional causality between governance and emissions suggested a dynamic interplay: good governance leads to lower emissions, while a healthier environment may create the social and political stability necessary for governance to flourish.

Furthermore, the positive relationship between trade openness and emissions ($\beta = 0.18$ in FMOLS; $\beta = 0.20$ in DOLS) pointed to the environmental costs associated with economic integration, lending support to the pollution haven hypothesis (Cole, 2004). However, the unidirectional causality from trade openness to



emissions suggested that trade policies can be strategically redesigned to promote sustainability without compromising economic benefits.

The diagnostic tests validated the robustness of these findings, confirming the absence of multicollinearity, heteroskedasticity, and autocorrelation, thereby ensuring the reliability of the statistical inferences.

6. Conclusion

This study set out to examine the integration of climate modelling, economic analytics, and policy design in promoting a sustainable blue economy. Using a robust quantitative methodology on a panel of emerging and coastal economies from 2005 to 2024, the research provided strong empirical evidence that these three pillars are not only interconnected but also fundamentally interdependent for achieving long-term sustainability.

The findings conclusively demonstrated that climate change, represented by the climate risk index, is a significant driver of environmental degradation, underscoring the urgent need to embed predictive climate tools into national economic planning. Concurrently, the research confirmed that while conventional economic growth and trade openness currently exert pressure on marine and coastal environments, this trajectory can be reversed through strategic investments in renewable energy and the establishment of strong, effective governance frameworks. The Granger causality analysis revealed that the path to sustainability is not linear but dynamic, characterized by feedback loops between green energy adoption and environmental quality, as well as between institutional strength and sustainability outcomes.

Crucially, the study validated the existence of a long-run equilibrium relationship among the key variables. This implies that the challenges facing the blue economy, climate vulnerability, economic pressures, and governance deficits, must be addressed simultaneously. Piecemeal, reactive policies are unlikely to succeed. Instead, a coordinated, data-driven, and integrated approach is essential.

In conclusion, this research affirmed that the vision of a resilient and sustainable blue economy is achievable, but it requires a fundamental shift from siloed decision-making to an integrative framework. By systematically combining climate forecasting, economic analytics, and adaptive policy design, nations can navigate the trade-offs between development and conservation, ensuring the long-term health and productivity of their ocean-based economies for future generations.

7. Recommendations

The research had given various valuable proposals to policymakers and stakeholders. First, governments ought to emphasize inclusion of climate modelling into national and regional tools in planning to allow them to become more resilient to environmental risks. Second, they had to encourage investments and sustainable, renewable energy in the ocean-based industries in order to decrease reliance on carbon based practices. Third, the policymakers ought to make governing institutions stronger by enhancing the standard of regulation, transparency and coordination within an institution to implement sustainability policies productively. Lastly, global co-operation and knowledge exchange could be promoted to respond to the global environmental issues and help in shifting to a blue economy that is sustainable.

8. Future Research Directions

The research had established a number of research areas in future. To begin with, primary data and case studies would be employed in future research to give more details about the country-specific issues and the effectiveness of the policies. Second, researchers can investigate how emerging technologies (artificial intelligence and big data analytics) can be used to improve climate modelling and economic forecasting. Third, additional studies might be conducted in the future, focusing on industry-specific effects in the blue economy, including fisheries, maritime transport, and coastal tourism in order to formulate more specific policy proposals. The relationship between social factors (community participation, and people awareness) and environmental sustainability could also be explored in the future. Such guidelines would help advance the vision of the blue economy and make possible the design of innovative and sustainable solutions.

Authors Contributions

All the authors participated in the ideation, development, and final approval of the manuscript, making significant contributions to the work reported.



Conflict of Interest Statement

The author declares no conflicts of interest.

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Ethical Approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Data Availability

The datasets generated during and analysed during the current study are available from the corresponding author on reasonable request.

References

- Abid, M. (2017). Does economic growth influence environmental degradation? *Environmental Science and Pollution Research*, 24(20), 16419–16430. <https://doi.org/10.1007/s11356-017-9304-2>
- Acheampong, A. O. (2018). Economic growth, CO₂ emissions and energy consumption. *Energy Policy*, 112, 313–322. <https://doi.org/10.1016/j.enpol.2017.10.029>
- Aghnyn, M., Rachmawati, R. N., Abdurrazzaq, A., Brahme, N., Dixit, A., & Hadap, A. (2024). Mapping blue economy potential using spatial statistical downscaling model. *International Journal of Hydrological and Environmental Sustainability*. <https://doi.org/10.58524/ijhes.v3i1.440>
- Ahn, K. H. (2024). Main contents and implications of the 2023 revision of the OECD Guidelines for Multinational Enterprises. *Journal of International Logistics and Trade*, 22(2), 80–92.
- Appiah, M. K., Ameko, E., Asiamah, T. A., & Duker, R. Q. (2023). Blue economy investment and sustainability of Ghana's territorial waters. *International Journal of Sustainable Engineering*. <https://doi.org/10.1080/19397038.2023.2195422>
- Askari, M., Ray, S., & Suri, S. (2026). Behavioral barriers to blue economy reform: A policy synthesis on ESG, emissions, and governance. *Marine Policy*, 184, 106938. <https://doi.org/10.1016/j.marpol.2025.106938>
- Bădîrcea, R. M., Manta, A. G., Florea, N. M., Puiu, S., Manta, L. F., & Doran, M. D. (2021). Connecting blue economy and economic growth to climate change. *Energies*, 14(15), 4600. <https://doi.org/10.3390/en14154600>
- Balsalobre-Lorente, D., Shahbaz, M., Roubaud, D., & Farhani, S. (2018). How economic growth influences CO₂ emissions. *Energy Economics*, 72, 119–131. <https://doi.org/10.1016/j.eneco.2018.03.017>
- Bano, S., Rafiq-uz-Zaman, M., & Khalid, N. (2024). Assessing health and environmental risks: Educational awareness on plastic usage and solid waste disposal in Bahawalpur. *Journal of Asian Development Studies*, 13(3), 917–929. <https://doi.org/10.62345/jads.2024.13.3.75>
- Burke, M., Hsiang, S. M., & Miguel, E. (2018). Global non-linear effect of temperature on economic production. *Nature*, 527, 235–239. <https://doi.org/10.1038/nature15725>
- Cole, M. A. (2004). Trade, the pollution haven hypothesis and environmental Kuznets curve. *Ecological Economics*, 48(1), 71–81. <https://doi.org/10.1016/j.ecolecon.2003.09.007>
- Danish, Baloch, M. A., & Wang, B. (2020). Role of renewable energy in reducing emissions. *Renewable Energy*, 150, 436–447. <https://doi.org/10.1016/j.renene.2019.12.066>
- Dietz, S., Rising, J., Stoerk, T., & Wagner, G. (2021). Economic impacts of climate tipping points. *Proceedings of the National Academy of Sciences*, 118(34). <https://doi.org/10.1073/pnas.2103081118>
- Gupta, V. P., Reyed, R. M., & Haghi, A. K. (2026). *The blue economy and environmental sustainability*. Springer. <https://doi.org/10.1007/978-3-032-13638-1>
- González-Espinosa, P. C., Singh, G. G., & Cisneros-Montemayor, A. M. (2025). Implementing the blue economy: Analysis of indicator interrelationships across countries and over time. *Ocean & Coastal Management*, 262, 107589. <https://doi.org/10.1016/j.ocecoaman.2025.107589>
- Hassan, S. T., Xia, E., Khan, N. H., & Shah, S. M. A. (2020). Economic growth, natural resources, and



- ecological footprint. *Science of the Total Environment*, 704, 135518. <https://doi.org/10.1016/j.scitotenv.2019.135518>
- Ibrahim, R. L., & Ajide, K. B. (2021). Renewable energy consumption and environmental sustainability. *Environmental Science and Pollution Research*, 28, 43767–43779. <https://doi.org/10.1007/s11356-021-13716-2>
- Hossain, M. A., Islam, M. N., Fatima, S., Kibria, M. G., Ullah, E., & Hossain, M. E. (2024). Pathway toward sustainable blue economy: Consideration of greenhouse gas emissions, trade, and economic growth in 25 nations bordering the Indian Ocean. *Journal of Cleaner Production*, 437, 140708. <https://doi.org/10.1016/j.jclepro.2024.140708>
- Kahn, M. E., Mohaddes, K., Ng, R. N., Pesaran, M. H., Raissi, M., & Yang, J. C. (2021). Long-term macroeconomic effects of climate change. *Energy Economics*, 104, 105624. <https://doi.org/10.1016/j.eneco.2021.105624>
- Khalid, N., Arshad, I., & Rafiq-uz-Zaman, M. (2024). Enhancing environmental education to promote pre-emptive smog mitigation strategies in urban areas of South Punjab: An overview. *Journal of Asian Development Studies*, 13(3), 956–964. <https://doi.org/10.62345/jads.2024.13.3.78>
- Khalid, N., Rafiq-uz-Zaman, M., Tahira, W., & Maqbool, M. (2024). Solid waste and environmental sustainability: Educational approaches to managing urban waste in Bahawalpur City. *Journal of Climate and Community Development*, 3(2), 155–170. <https://joccd.com/index.php/joccd/article/view/50>
- Le, H. P., Ozturk, I., & Abokyi, E. (2020). Trade openness and environmental quality. *Environmental Science and Pollution Research*, 27, 1–14. <https://doi.org/10.1007/s11356-020-08085-8>
- Mohiuddin, D. (2026). Adaptive marketing systems and consumer feedback loops: Implications for market development in emerging economies. *Journal of Business Insight and Innovation*, 5(1), 37–48.
- Mohiuddin, D. (2025). HR tech adoption in digital banking: Implications for workforce development and financial sector growth in emerging economies. *Journal of Business Insight and Innovation*, 4(2), 77–90.
- Mohiuddin, D. (2024). Algorithmic hyper-personalization: The double-edged sword of predictive personalization—An empirical investigation. *Journal of Engineering and Computational Intelligence Review*, 2(2), 82–94.
- Osman, Y., & Elmakawi, Z. I. (2025). Blue economy and renewable energy nexus. *Discover Sustainability*. <https://doi.org/10.1007/s43621-025-02172-y>
- Osman, Y., & Elmakawi, Z. I. (2025). Implication of blue economy and renewable energy on CO₂ emissions. *Discover Sustainability*. <https://doi.org/10.1007/s43621-025-02172-y>
- Ospina, D., Mirazo, P., Allan, R. P., Basnett, S., Bastos, A., Bhattarai, N., ... & Zhu, S. (2026). Ten new insights in climate science 2025. *Global Sustainability*, 9, e6.
- Rafiq-uz-Zaman, M. (2023). Bridging CPEC-driven industrial growth and skill-based education in Pakistan: A systematic review. *Journal of Business Insight and Innovation*, 2(1), 55–78. <https://insightfuljournals.com/index.php/JBII/article/view/57>
- Rafiq-uz-Zaman, M., Khalid, N., Faridi, M. Z., & Khan, Z. A. (2024). Smog mitigation and climate resilience in Pakistan: A policy-centric review of strategies and challenges. *Social Sciences Spectrum*, 3(4), 302–317. <https://doi.org/10.71085/sss.03.04.175>
- Rodriguez-Pardo, C., Daumas, L., Chiani, L., & Tavoni, M. (2025). Climate-economic modeling under uncertainty. *arXiv*. <https://doi.org/10.48550/arXiv.2505.13264>
- Sarker, S., Hussain, F. A., Assaduzzaman, M., & Failler, P. (2019). Blue economy and climate change: Bangladesh perspective. *Journal of Ocean and Coastal Economics*, 6(2). <https://doi.org/10.15351/2373-8456.1105>
- Shahbaz, M., Mallick, H., Mahalik, M. K., & Sadorsky, P. (2017). The role of globalization in energy–environment nexus. *Energy Economics*, 64, 538–549. <https://doi.org/10.1016/j.eneco.2017.04.007>
- Sinha, A., Shahbaz, M., & Balsalobre-Lorente, D. (2021). Impact of institutional quality on environmental performance. *Journal of Cleaner Production*, 279, 123814.



- <https://doi.org/10.1016/j.jclepro.2020.123814>
Vrontisi, Z., Charalampidis, I., Lehr, U., Meyer, M., Paroussos, L., Lutz, C., & León, C. J. (2022). Macroeconomic impacts of climate change on blue economy sectors. *Climatic Change*, 170, 27. <https://doi.org/10.1007/s10584-022-03310-5>
- Wuwung, L., Croft, F., Benzaken, D., Azmi, K., Goodman, C., Rambourg, C., & Voyer, M. (2022). Global blue economy governance. *Frontiers in Marine Science*. <https://doi.org/10.3389/fmars.2022.1043881>
- Zhang, Y., Jin, W., & Chevallier, J. (2021). Carbon emissions and trade openness nexus. *Energy Policy*, 150, 112123. <https://doi.org/10.1016/j.enpol.2021.112123>

