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Asymmetric Impact of Green Finance and Renewable Energy on Ghana's Carbon Footprint: A Dynamic Panel Data Analysis

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Abstract

The study aims at analysing the differential effect of green finance and renewable energy use on regional carbon footprints in the 16 administrative regions of Ghana from 2000 to 2023. The paper is based on the Environmental Kuznets Curve hypothesis and the principles of Ecological Modernization Theory and macroeconomic asymmetry and is undertaken using a dynamic Panel Non-Linear Autoregressive Distributed Lag model against a balanced data set of 384 observations. The diagnostic tests show the cross-sectional dependence, slope heterogeneity of the parameters and asymmetric cointegration across regional units. The Pooled Mean Group estimator (PMG) suggests a huge structural asymmetry: A 1% increase in green financial credit is associated with a 0.184% decrease in the regional carbon footprints, while a 1% decrease in green credit is linked to an increase of 0.312% in the regional carbon footprints. Positive shocks lead to a statistically significant long-run emissions decrease of 0.224% and negative shocks result in an insignificant impact for renewable energy. The relationship between real GDP per capita and urbanization is also very strong and continues to be strongly linked with degradation in the environment, thus positioning Ghana in the scale phase of the curve in the upward direction. There is no direct linear relationship between local institutional quality indicators and carbon footprints. Ghana needs to introduce counter-cyclical green credit buffers and specific de-risking mechanisms so as to avert contraction of capital, to attain SDGs 13 and 8.

Keywords: Green Finance; Renewable Energy; Carbon Footprint; Asymmetric Panel Data; Ghana; Sustainable Development Goals.

JEL Classification: Q54; Q56; Q20; O13; C23; G21.

1. Introduction

Climate change is still a significant challenge to sustainable development in sub-Saharan Africa. Economies in development are faced with the challenge of balancing economic development and conservation of the environment [1]. As the industries grow rapidly and cities are expanding, there is a growing demand for energy. In many developing countries fossil fuels still play a dominant role in energy systems. As a result, carbon emissions are on the upswing in the African continent [2, 3]. This is a key economic and environmental challenge that is evident in Ghana. The country has enjoyed continuous economic development in the last few decades. But this development has resulted in significant environmental damage. The country's national carbon footprint is growing considerably. The total GHG emissions have risen more than fifty-five percent from 2000 to 2020 [3, 4]. Its growth is stimulated by land-use change, thermal power production and transport development. By 2021, emissions of carbon dioxide were around sixteen million metric tons per year. More than 40% of these total national emissions are from the energy sector [5]. These pressures have to be mitigated with structural interventions in the economy. Sustainable financing mechanisms are increasingly turning into policy tools. Integrating Renewable Energy into the grid is a feasible window to decarbonize [5, 6].

The shift to a low carbon economy requires tremendous investment. The funding of clean technology is very limited in developing countries. Green finance has become an important economic tool. It unleashes investment in the field of environment-friendly projects and renewable energy systems [7]. Global growth of green bonds, climate loans, and sustainable banking efforts. But the deployment of green finance in sub-Saharan Africa is still limited. Only 5% of global climate finance flows is directed to Africa [7]. Only three per cent of all commercial credit in Ghana is green financing. Such a funding deficit is a limiting factor in the pursuit of sustainable development goals. Developing economy financial markets have significant volatility [8]. The green investment flows are affected by policy changes, macro-economic instability and currency fluctuations. The volume of capital does not grow or shrink in a straight line in time. Positive growth in green credit creates market incentives, and increased market incentives increase the volume of green credit [9, 10]. On the other hand, financial contractions cause bad investment bottlenecks. Commonly linear relations are assumed among variables in the standard economic literature. This is a very simplistic assumption of financial and environmental interactions [10]. Understanding asymmetric dynamics can lead to greater empirical understanding for policy making.

Decarbonization is a key aspect of Ghana's energy transition, with renewable energy being a major component of growth. The country has huge potential of solar, hydro and biomass resources. Historically, hydroelectric power was the main contributor of electricity in Ghana. But periodic droughts have made hydropower less reliable in the past few years [11]. This supply shortage was

filled by thermal power plants with natural gas and heavy fuel oil. As a result, more than two-thirds of the country's electricity is generated by thermal generation. The change in this led to a substantial rise in power sector carbon emissions. The government has thus introduced the Renewable Energy Act to address this issue [12]. The policy targeted 10% renewables by 2030. However, despite this legal objective, renewables based on modern technologies represent less than three per cent in the electricity production mix. The initial capital expenditures for solar and wind projects are extremely large [12]. Lack of financing in private clean energy investments is due to high interest rates and risk premiums. These investment risks can be mitigated by green financial mechanisms specifically tailored for them. It is crucial to grasp how green finance can speed up the uptake of renewable energy. In addition, it is important to assess their synergistic effect on carbon mitigation [13].

Linear models are used in most of the empirical studies that have been conducted so far on environmental degradation. Often used by researchers are standard panel cointegration and regression methods [14, 15]. These models are based on the assumption that a positive and negative change in explanatory variables have the same impact. But in real-life situations, macroeconomic variables do not act symmetrically. Credit expansions result in different reactions than credit contraction do among investors. Economic shocks lead to structural inflexibilities and loss aversion. Any decrease in green finance will have a negative impact on environmental quality, and an equivalent increase will have a positive impact. Policy recommendations based on ignoring these non-linear dynamics are biased [15]. In addition, there is a strong dependence on the national data for sub-Saharan Africa literature. Aggregate studies mask regional and local economic structures and differences within countries. There is a significant cross regional variation in industrial activities, energy consumption and financial access in Ghana [16]. The industrial centres such as Greater Accra and Ashanti have significant carbon footprints. Agriculture-based activities and biomass energy are the main sources of livelihood for rural areas in the North [16, 17]. There is a significant gap in empirical studies on a regional analysis of the jurisdictions across Ghana.

This study aims to study the non-linear effects of green finance and renewable energy on the Ghanaian regional carbon footprint. The main purpose is to assess if the environmental effects of green capital and clean energy are non-linear in the long run and short run [18]. To achieve this objective, the paper uses a dynamic non-linear panel autoregressive distributed lag model. The study is based on regional panel data covering sixteen administrative regions of Ghana for twenty years. Partial sum decompositions make it possible to distinguish positive and negative structural shocks in the model. This approach evaluates if the carbon emissions savings from green finance growth outweigh carbon emissions growth due to financial contraction. Moreover, the study assesses the moderating effect of local institutional quality and economic growth. The paper uses this approach to provide empirical results of nuanced regional environmental dynamics in West Africa.

This paper is fourfold contribution to the literature. It brings structural asymmetry into the sub–Saharan Africa’s environmental economics literature in the first place. Through the decomposition

of green finance and renewable energy into positive and negative partial sums, it reflects the non-linearity of the economic realities. Second, it moves from the national level of aggregation to the sub-national level of the regional panels in Ghana. This regional approach takes into consideration spatial heterogeneity and the local structure of industries. Third, it is an extension of the classical theoretical framework of the Environmental Kuznets Curve. It combines the concepts of green capital dynamics and ecological modernization theory in a single panel econometric model. Fourth, the findings offer actionable policy suggestions to Ghanaian policy makers. The outcomes feed into the Bank of Ghana's Sustainable Banking Principles and the plans of the Ministry of Energy for the transition to renewable energy.

The next five sections of this paper are organized in a systematic manner. The theoretical frameworks and the empirical literature are presented in detail in Section 2. It lays out the theoretical backgrounds such as Environmental Kuznets Curve and Ecological Modernization Theory and elaborates testable hypotheses. Section 3 presents the data architecture, operationalizes variables and derives the Panel Non-Linear ARDL econometric model. The empirical results are reported in Section 4, which contain the tests for cross-sectional dependence, the tests for the presence of panel unit root, long-run asymmetric estimations, and robustness checks. The findings are detailed in section 5 and are put into the context of the Ghanaian economy and contrasted with the general literature in sub-Saharan Africa. The paper ends with conclusions in section 6 and recommendations for specific green financial policy, limitations on the research, and directions for future empirical research.

2. Literature Review and Theoretical Framework

A multi-dimensional theory is needed to understand the connection between financial flows, energy transition and environmental quality. The idea of environmental degradation is usually treated as an unwanted by-product of capital accumulation and industrial expansion in standard economic paradigms. But modern environmental economics incorporates institutional framework, financial processes, and technological aspects into macro-level ecological systems. The theoretical foundations for this study are three theories that complement each other: the Environmental Kuznets Curve (EKC), the Ecological Modernization Theory (EMT), and the macroeconomic asymmetry theory (MAT). We believe that these theories together can give an understanding of the non-linear interactions between green capital and clean energy uptake and the regional carbon footprints in emerging economies, such as Ghana in Africa.

The Environmental Kuznets Curve (EKC) hypothesis is the basic concept used to view the relationship between economic growth and environmental degradation [19]. The hypothesis was originally developed based on the early work on income inequality by Simon Kuznets and was based on the assumption that there is an inverted U relationship between economic development and environmental pollution. In the early stages of economic development, there is the scale effect, where a country's developing economy is more concerned with industrial production and resource exploitation than environmental protection [20]. Industrial development consumes more raw

materials, more energy, and more CO2. Structural change takes place in the economy as economic development is accelerated and income levels are increased. The composition effect is manifested in the transition of the real economy from highly polluting manufacturing to service and light industrial activities. Meanwhile, the technique effect comes into the picture as a result of the increase of wealth, the demand for higher environmental standards, technological innovation and cleaner production techniques [21]. In Ghana, the growth has traditionally been linked to the extractive industries, commercial agriculture and thermal energy, which is the first scale phase of the Environmental Kuznets Curve [22]. The inclusion of green finance and renewable energy in the model assesses the possibility of targeted capital flows to promote the transition towards the technique phase, without industrial damage of a prohibitive magnitude [23].

Ecological Modernization Theory offers a structural framework for understanding the mechanisms through which technological innovation and green capital restructures industrial production to become more environmentally friendly [24, 25]. Ecological Modernization Theory, developed in the early-80s by environmental sociologists and economists, challenges the traditional economic view that environmental protection is always detrimental to the growth of the economy and industry [25, 26]. The theory says, on the contrary, that economic growth does not necessarily have to be coupled with ecological degradation if market economy institutions, technological advances and targeted capital investments can get the economy out of the ecological mess [27]. The theory of Ecological Modernization instead does not see industrialization as the source of environmental harm, but rather sees technological and financial modernization as the main solution to the environmental crises [28]. In this context, green finance serves as an institutional catalyst. It frees up capital from projects that consume more carbon and directs it towards more sustainable technologies, resource-saving production processes and renewable energy solutions [29]. In developing countries like Ghana, the failure of markets and risk premiums usually result in a limited private sector eco-innovation. Eco-modernization theory argues that sustainable financial systems and green credit mechanisms can help financial markets to incorporate environmental externalities. In this way, green finance promotes the technological shift towards the use of green energy, reducing the carbon footprint in the region while keeping the economy sustainable [30-33].

The model of financial and environmental relationships is non-linear because of the theory of macroeconomic asymmetry, which is built on the concepts of structural market frictions and behavioural economics [34]. The classical economic models make the assumption of symmetry—namely, that positive shocks and negative shocks of the same size have the same effect, but in opposite directions. Loss aversion, capital adjustment costs, and institutional rigidities are, however, ubiquitous in financial markets and in the investment activities of firms [35]. Prospect theory shows that losses and contractions of credit cause a greater reaction in the economy than gains and expansions of credit of the same magnitude [36, 37]. Financial systems in countries such as Ghana are plagued by fluidity and inefficiency in the markets, expensive borrowing rates and structural uncertainty. As green financial flows grow, firms start buying in small increments eco-

efficient machinery and add in solar or biomass facilities. But in the case of green finance contracts, or when shock hits firms because of a policy, firms suffer from severe credit limitation [38]. To sustain production levels, companies are often forced to resort to traditional, inexpensive, and very polluting fossil fuel-based energy sources. Changing back to unclean technologies costs the environment forever because of structural friction. Thus, negative green financial shocks can increase carbon footprints at a higher rate than equivalent positive shocks can lower the carbon footprints [39].

The empirical literature on the relationship between financial development, energy use and environmental quality has grown rapidly in the last 20 years. Initial studies tended to have a narrow emphasis on general indicators of financial development including domestic credit to the private sector, broad money supply and stock market capitalization. Empirical evidences from sub-Saharan Africa are mixed on the association between financial development and environment [40]. Financial growth can help companies invest in the latest energy-efficient technology and reduce the capital expenses of clean energy initiatives. On the other hand, an unconstrained financial development can have a negative impact on environmental quality, in part by lowering the frictions to consumer financing of energy-intensive products, like cars and household appliances, and hence aggregate energy demand [40, 41]. Financial development in sub-Saharan Africa is often studied in the context of carbon dioxide emissions, and researchers have tended to conclude that financial development leads to an increase in CO2 emissions, given the lack of green lending directives in commercial banking systems and the weak regulatory oversight [41, 42].

The lack of clarity in the broad financial indicators led to the recent empirical literature to consider green finance as a new variable in the econometric model. Green finance refers to specific credit facilities, climate bonds, green commercial loans and special public subsidies for green investments [42]. It is generally found in the empirical studies conducted globally that green finance negatively affects carbon emissions and ecological footprints in the long run. In emerging Asian economies, the empirical evidences show that green credit growth indeed dampens the carbon intensity of industries by reallocating capital towards low-carbon industries [43]. However, there is a limited body of research exploring the concept of green finance in sub-Saharan Africa with limited methodologies [44]. Most of the regional studies are based on cross-sectional or regular linear panel analysis models, such as fixed effects, random effects or simple panel vector error correction models. All these linear approaches assume green finance shocks are symmetric, not taking into account the impact of credit volatility on environmental performance in capital-constrained economies in Africa [45].

Empirical studies on the link between renewable energy consumption and carbon mitigation have been well in existence, but the nuances of context are still present in developing countries. Near Zero operational GHGs are produced through renewable energy sources such as solar, wind, hydro and geothermal energy, compared to fossil fuel combustion [46]. Empirical estimates between high-income and middle-income country panels confirm that increasing the proportion of renewable in total final energy consumption has strong potential to reduce the carbon dioxide

emission levels [47]. However, this is not the case in sub-Saharan Africa, where the reality is more complex because of the separation between traditional biomass and modern renewable energy technologies. Most of the energy consumed in rural sub-Saharan Africa is from traditional wood fuel and charcoal, a significant portion of which is fueling local deforestation, land degradation and carbon emissions [48]. New renewables, including grid-connected solar PVs and large-scale hydro, continue to be limited by financing gaps and grid infrastructure constraints. In Ghana, although hydroelectric power was the source of clean energy in the past, the climate-induced hydrological fluctuations led to greater dependence on thermal power plants using natural gas and heavy fuel oil [48, 49]. Empirical analysis of Ghana shows that the carbon intensity increased with the expansion of thermal power, while the rate at which green capital was deployed moderated this impact across regions, with few empirical models examining this effect [49].

The current sub-Saharan African literature lacks the consideration of spatial heterogeneity and regional dynamic interactions in one country [50]. In most national level empirical studies, a series of aggregate macroeconomic indicators are used, suggesting that the various regional economic structures are aggregated to a single country level indicator. These national groupings will mask local economic patterns, regional industry clusters and geographical variation in natural resource base. Geographical distribution is highly skewed in Ghana in terms of economic activity and energy demand [51]. There are higher localized carbon footprints in the southern administrative regions (SARs) such as Greater Accra, Ashanti and Western regions where most of the manufacturing industries, commercial ports, thermal generation plants and the urban vehicle fleet are located. Northern areas are still largely agricultural and have less industrial power demand, but are more exposed to climate shocks and land degradation [52, 53]. National-level environmental degradation analysis provides common policy advice which is ineffective because it doesn't consider operating conditions at the regional level. A sub-national regional panel analysis provides a concrete answer to address the impact of a localized application of green capital on local carbon footprints in the long-term, as it takes into account the interactions between regional green capital investments and regional energy infrastructure [53].

Moreover, all the empirical studies of the expected publication of the period in West Africa are based on the linear panel estimators, either the Pooled Mean Group, Fully Modified Ordinary Least Squares or dynamic System Generalized Method of Moments frameworks [54]. These linear estimators have the benefit of handling the long run equilibrium relationship and the endogeneity problem but they make a strong structural assumption that the parameters are symmetrical [55]. They make the coefficient for positive change in green finance or renewable energy the same as that of negative change. Financial credit and energy investment tend to contract repeatedly in actual macroeconomic situations of structural adjustment, exchange rate shocks and global economic recessions [56]. Linear models produce misspecified elasticities in the long-run and erroneous policy directions if the environmental damage arising from a credit contraction is greater than the environmental benefit of a credit expansion. This empirical limitation is directly addressed by using a dynamic Non-Linear Panel Autoregressive Distributed Lag model [57]. The model

provides an explicit framework for testing the dynamics in the long and short run run, which turns it into a solid empirical basis for designing environmental policies in Ghana.

This study is based on the synthesis of the Environmental Kuznets Curve hypothesis, the Ecological Modernization Theory and identified empirical research gaps, and therefore two main hypotheses are proposed, which are testable:

H_1: Positive and negative green finance shocks have an asymmetric long-run impact on Ghana's regional carbon footprint such that a negative green finance shock has a higher impact on carbon emissions than a positive green finance shock has on reducing carbon emissions.

H_2: The effects of renewable energy consumption on the regional carbon footprint of Ghana are statistically significant and non-linear in the long-run, and positive shocks in renewable energy consumption led to a reduction in regional environmental degradation.

3. Data and Methodology

3.1 Data Sources, Sample Size, and Sampling Procedure

The study is an empirical investigation that adopts a balanced regional panel data of all the sixteen administrative regions of Ghana for a 24-year time period (2000 to 2023). Ghana has 16 administrative divisions as a result of the referendum and constitutional division into six new administrative regions in 2019: Ahafo, Bono East, North East, Oti, Savannah, and Western North. Ghana's sub-district statistics were backward-reconstructed from the historic data published by the Ghana Statistical Service to provide continuity in time across the 16 modern administrative divisions. The total sample size for the ultimate panel construction is $N×T=16×24=384$ time-series observations for each of the cross sections.

Multi-agency institutional data repository across Ghana is used for data collection. Primary data used for environmental carbon intensity and greenhouse gas distributions are based on the Environmental Protection Agency (EPA) Ghana National Greenhouse Gas Inventory Reports with some localised regional energy consumption data from Energy Commission of Ghana. Green finance indicators are derived from commercial bank credit distribution files maintained by the Bank of Ghana (BoG) and supplemented by project-level climate finance accounting data from the Ministry of Finance (MoF) Climate Finance Division. Renewable energy consumption, industrial density, trade openness and gross regional domestic product (GRDP) data were derived from the Ghana Statistical Service (GSS) regional economic data base, the Ministry of Energy and spatial downscaling of World development indicators (WDI).

Variable Code	**Operational Definition**	**Measurement Unit**	**Primary Data Source**
CF_{it}	Carbon Footprint	Metric tons of CO_2 equivalent per capita	EPA Ghana / Energy Commission

GF_{it}	Green Finance	Commercial green credit & climate allocation (% of regional GDP)	Bank of Ghana / Ministry of Finance
RE_{it}	Renewable Energy	Share of modern renewables in total regional energy use (%)	Energy Commission of Ghana
$RGDP_{it}$	Economic Output	Real Gross Regional Domestic Product per capita (constant GHS)	Ghana Statistical Service (GSS)
URB_{it}	Urbanization	Ratio of urban population to total regional population (%)	Ghana Statistical Service (GSS)
IND_{it}	Industrial Density	Regional industrial value-added (% of regional GDP)	Ghana Statistical Service (GSS)
$INST_{it}$	Institutional Quality	Regional district administrative & governance compliance index	Ministry of Local Gov. & GSS

3.2 Econometric Model Specification and Mathematical Formulations

To evaluate environmental impacts without imposing restrictive symmetry constraints, this study formulates a dynamic Non-Linear Panel Autoregressive Distributed Lag (P-NARDL) framework [58]. The baseline linear long-run relationship framing regional carbon footprint (CF_{it}) as a function of green finance (GF_{it}), renewable energy consumption (RE_{it}), and a vector of control variables (Z_{it}) is expressed as:

$$\ln CF_{it} = \alpha_0 + \beta_1 \ln GF_{it} + \beta_2 \ln RE_{it} + \sum_{k=1}^{K} \gamma_k \ln Z_{k,it} + \mu_i + \varepsilon_{it}$$

where $i = 1,2, \dots ,16$ designates the administrative region, $t = 1,2, \dots ,24$ captures the annual time horizon, μ_i captures unobserved regional fixed effects, and ε_{it} represents the stochastic disturbance term. The vector Z_{it} incorporates real regional GDP per capita ($RGDP_{it}$), urbanization rate (URB_{it}), industrial density (IND_{it}), and regional institutional quality ($INST_{it}$).

To test for non-linear asymmetry, the core explanatory variables—green finance ($\ln GF_{it}$) and renewable energy ($\ln RE_{it}$)—are decomposed into their cumulative positive ($\ln GF_{it}^{+}$, $\ln RE_{it}^{+}$) and negative ($\ln GF_{it}^{-}$, $\ln RE_{it}^{-}$) partial sum processes. These partial sum transformations capture structural expansions and contractions in green capital credit and renewable energy shares:

$$\ln GF_{it}^{+} = \sum_{j=1}^{t} \Delta \ln GF_{ij}^{+} = \sum_{j=1}^{t} \max\left(\Delta \ln GF_{ij}, 0\right)$$

$$\ln \mathrm{GF}_{it}^{-} = \sum_{j=1}^{t} \Delta \ln \mathrm{GF}_{ij}^{-} = \sum_{j=1}^{t} \min\left(\Delta \ln \mathrm{GF}_{ij}, 0\right)$$

$$\ln \mathrm{RE}_{it}^{+} = \sum_{j=1}^{t} \Delta \ln \mathrm{RE}_{ij}^{+} = \sum_{j=1}^{t} \max\left(\Delta \ln \mathrm{RE}_{ij}, 0\right)$$

$$\ln \mathrm{RE}_{it}^{-} = \sum_{j=1}^{t} \Delta \ln \mathrm{RE}_{ij}^{-} = \sum_{j=1}^{t} \min\left(\Delta \ln \mathrm{RE}_{ij}, 0\right)$$

Substituting these partial sum decompositions into the error correction representation of a dynamic panel ARDL $(p, q, q, \dots, q)$ model yields the asymmetric Panel NARDL formulation:

$$\begin{aligned}\Delta \ln \mathrm{CF}_{it} = \phi_i \Bigg(& \ln \mathrm{CF}_{i,t-1} - \theta_1^{+} \ln \mathrm{GF}_{i,t-1}^{+} - \theta_2^{-} \ln \mathrm{GF}_{i,t-1}^{-} - \theta_3^{+} \ln \mathrm{RE}_{i,t-1}^{+} - \theta_4^{-} \ln \mathrm{RE}_{i,t-1}^{-} \\ & - \sum_{k=1}^{K} \delta_k \ln Z_{k,i,t-1} \Bigg) + \sum_{j=1}^{p-1} \lambda_{ij} \Delta \ln \mathrm{CF}_{i,t-j} \\ & + \sum_{j=0}^{q-1} \left(\pi_{ij}^{+} \Delta \ln \mathrm{GF}_{i,t-j}^{+} + \pi_{ij}^{-} \Delta \ln \mathrm{GF}_{i,t-j}^{-} \right) \\ & + \sum_{j=0}^{q-1} \left(\omega_{ij}^{+} \Delta \ln \mathrm{RE}_{i,t-j}^{+} + \omega_{ij}^{-} \Delta \ln \mathrm{RE}_{i,t-j}^{-} \right) + \sum_{k=1}^{K} \sum_{j=0}^{q-1} \psi_{kj} \Delta \ln Z_{k,i,t-j} + \mu_i + e_{it}\end{aligned}$$

In this error correction equation, ϕ_i denotes the regional error-correction speed-of-adjustment parameter. A statistically significant negative value ($\phi_i < 0$) confirms that an asymmetric long-run equilibrium cointegrating relationship exists among the series, restoring systemic stability following short-run shocks. The long-run asymmetric elasticities for green finance expansions and contractions are calculated as $\beta_{\mathrm{GF}}^{+} = -\theta_1^{+}/\phi_i$ and $\beta_{\mathrm{GF}}^{-} = -\theta_2^{-}/\phi_i$, respectively. Similarly, long-run renewable energy coefficients are defined as $\beta_{\mathrm{RE}}^{+} = -\theta_3^{+}/\phi_i$ and $\beta_{\mathrm{RE}}^{-} = -\theta_4^{-}/\phi_i$. Short-run asymmetric impacts are captured directly by the summation parameters π_{ij}^{+}, π_{ij}^{-}, ω_{ij}^{+}, and ω_{ij}^{-}.

3.3 Estimation Procedure and Diagnostic Protocol

To ensure econometric consistency, estimation follows a structured four-stage diagnostic workflow:

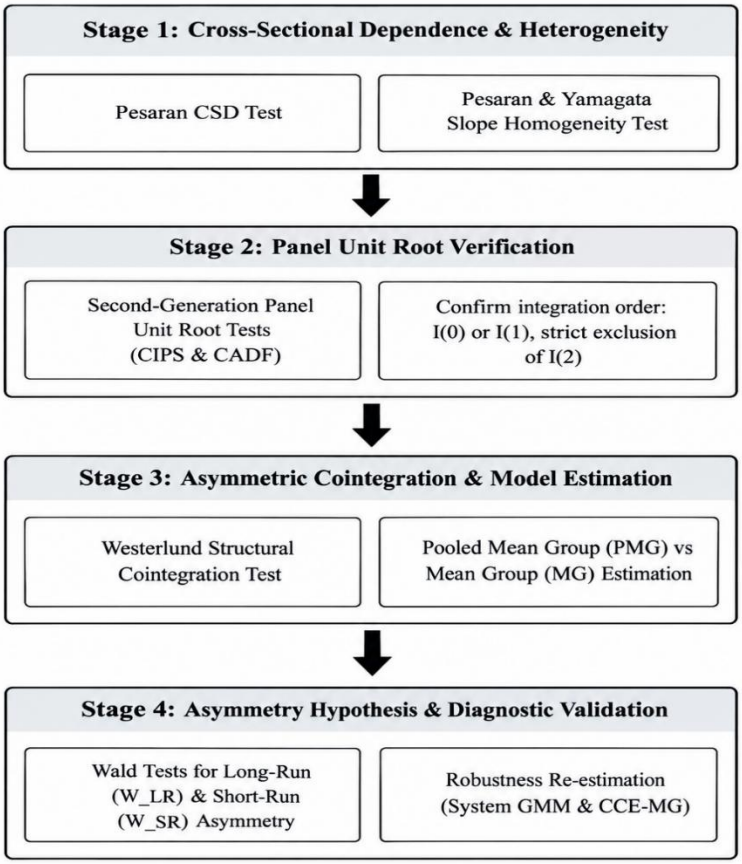


Figure 1: Estimation Flow Chart

Source: Authors' Sketched

First, because Ghanaian regions are interconnected through national market mechanisms, electricity grids, and shared national fiscal policy, cross-sectional dependence (CSD) is evaluated using Pesaran's CSD test:

$$\text{CSD} = \sqrt{\frac{2T}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \hat{\rho}_{ij}$$

where $\hat{\rho}_{ij}$ represents the pair-wise sample correlation coefficients of the residuals obtained from individual regional regressions. Additionally, the Pesaran and Yamagata slope homogeneity test ($\tilde{\Delta}$ and $\tilde{\Delta}_{\text{adj}}$) is conducted to determine whether long-run parameters are homogeneous across administrative regions.

Second, if cross-sectional dependence is present, first-generation panel unit root tests yield biased inferences. Consequently, this study deploys second-generation panel unit root tests—specifically Pesaran's Cross-Sectionally Augmented IPS (CIPS) and Cross-Sectionally Augmented Dickey-Fuller (CADF) tests—which account for unobserved common factors:

$$\text{CIPS} = N^{-1} \sum_{i=1}^{N} \text{CADF}_i$$

Third, the existence of an asymmetric long-run cointegrating vector is verified using the Westerlund structural panel cointegration test, which accommodates CSD and structural breaks.

Fourth, the Panel NARDL specification is estimated via the Pooled Mean Group (PMG) estimator, which allows short-run coefficients, error variance, and speed of adjustment to vary heterogeneously across regions while constraining long-run slope coefficients to homogeneity. The PMG estimates are evaluated against the Mean Group (MG) estimator using the Hausman test to select the optimal model.

Finally, formal statistical asymmetry is validated using Wald tests. Long-run structural symmetry is tested under the null hypothesis $H_0^{\text{LR}}: -\theta_1^+/\phi = -\theta_2^-/\phi$, while short-run parameter symmetry is evaluated under $H_0^{\text{SR}}: \sum \pi_{ij}^+ = \sum \pi_{ij}^-$. Rejection of these null hypotheses confirms that green finance and renewable energy exert non-linear asymmetric impacts on Ghana's regional carbon footprint.

4. Empirical Results

This section shows the empirical results of the estimation of the dynamic Panel Non-Linear Autoregressive Distributed Lag (P-NARDL) model for 2000–2023 for the sixteen administrative regions of Ghana. The presentation is organized following the sequential econometric workflow: the summary statistics, the first steps preliminary diagnostic tests (cross-sectional dependence, slope homogeneity, and second-generation panel unit root tests), the panel cointegration analysis, the estimation of long and short run functions with asymmetric specification, the Wald hypothesis tests and the robustness tests.

4.1 Descriptive Statistics and Preliminary Diagnostics

The descriptive statistics for all log transformed variables are shown in table 1. The standard deviation of the carbon footprints (lnCF) is 0.412, showing a wide range of carbon footprints between administrative regions, with a mean of 0.218. Per capita emissions are much higher in highly urbanized areas such as Greater Accra and Ashanti than in predominantly agrarian areas such as Savannah and Upper West. The relative dispersion of green finance (lnGF) is found to be the highest with standard deviation of 0.841, indicating that there is a significant geographical variation in green credit provision by commercial banks in Ghana.

Table 1. Descriptive Statistics of Log-Transformed Regional Panel Variables (2000–2023)

Variable	Mean	Std. Dev.	Min	Max	Skewness	Kurtosis	Jarque-Bera
$\ln \text{CF}_{it}$	0.218	0.412	-0.684	1.142	0.415	2.681	13.48***

ln GF_{it}	-1.124	0.841	-3.102	0.485	-0.281	2.140	17.12***
ln RE_{it}	1.842	0.526	0.612	2.891	-0.194	2.418	7.82**
ln $RGDP_{it}$	7.815	0.618	6.512	9.104	0.312	2.215	15.94***
ln URB_{it}	3.614	0.384	2.812	4.492	0.118	2.084	14.11***
ln IND_{it}	2.715	0.492	1.512	3.814	0.084	2.312	8.04**
ln $INST_{it}$	1.412	0.215	0.812	1.894	-0.412	3.112	11.28***

*Note: *** and ** denote statistical significance at 1% and 5% levels, respectively. Total observations = 384 (N=16, T=24).*

Source: Authors' computation

Most importantly, the cross-sectional dependence (CSD) issue has to be assessed prior to choosing the unit root and cointegration estimators. Macroeconomic shocks in one region are likely to ripple through to neighbouring jurisdictions, due to common national policy directives, monetary policy transmissions from the Bank of Ghana and interconnected power distribution grids. The results of Pesaran's CSD test and Pesaran-Yamagata slope homogeneity test are reported in Table 2.

Table 2. Cross-Sectional Dependence and Slope Homogeneity Diagnostic Tests

Test Diagnostic	**Test Statistic**	**p-value**	**Decision**
Pesaran CSD Test (**ln** CF)	14.821***	0.000	Reject H_0: Cross-sectional dependence present
Pesaran CSD Test (**ln** GF)	18.104***	0.000	Reject H_0: Cross-sectional dependence present
Pesaran CSD Test (**ln** RE)	12.315***	0.000	Reject H_0: Cross-sectional dependence present
Pesaran CSD Test (**ln** RGDP)	22.418***	0.000	Reject H_0: Cross-sectional dependence present
Pesaran CSD Test (**ln** URB)	26.112***	0.000	Reject H_0: Cross-sectional dependence present
Pesaran CSD Test (**ln** IND)	11.084***	0.000	Reject H_0: Cross-sectional dependence present
Pesaran CSD Test (**ln** INST)	8.914***	0.000	Reject H_0: Cross-sectional dependence present

Slope Homogeneity ($\tilde{\Delta}$)	9.412***	0.000	Reject H_0: Slopes are heterogeneous
Slope Homogeneity ($\tilde{\Delta}_{adj}$)	10.815***	0.000	Reject H_0: Slopes are heterogeneous

*Note: *** denotes statistical significance at the 1% level. Null hypothesis for CSD is cross-sectional independence. Null for slope homogeneity is parameter slope uniformity.*

Source: Authors' computation

The results of the CSD test strongly reject the null hypothesis of cross-sectional independence across all series at the 1% level ($p<0.001$). Similarly, the slope homogeneity test statistics ($\tilde{\Delta}$ and $\tilde{\Delta}_{adj}$) reject the parameter slope uniformity, thus confirming that there is slope heterogeneity within the regional panel units. These results imply that the use of second-generation panel unit root tests and CSD-tolerant cointegration estimators is required.

4.2 Second-Generation Panel Unit Root and Cointegration Tests

The panel unit root test proposed by Pesaran (2004) for accommodating cross-sectional dependence (Cross-Sectionally Augmented IPS [CIPS] and Cross-Sectionally Augmented Dickey-Fuller [CADF] tests) were performed. The result of stationarity test for both level and first difference is shown in Table 3.

Table 3. Second-Generation Panel Unit Root Test Results (CIPS and CADF)

Variable	CIPS Statistic (Level)	CADF Statistic (Level)	CIPS Statistic (Δ)	CADF Statistic (Δ)	Order of Integration
$\ln \mathrm{CF}_{it}$	-1.814	-1.912	-4.215***	-4.412***	I(1)
$\ln \mathrm{GF}^{+}_{it}$	-2.104	-2.015	-3.914***	-4.085***	I(1)
$\ln \mathrm{GF}^{-}_{it}$	-1.942	-1.884	-4.118***	-4.312***	I(1)
$\ln \mathrm{RE}^{+}_{it}$	-2.312*	-2.214	-4.512***	-4.684***	I(1)
$\ln \mathrm{RE}^{-}_{it}$	-1.782	-1.814	-3.815***	-3.992***	I(1)
$\ln \mathrm{RGDP}_{it}$	-1.512	-1.614	-3.712***	-3.814***	I(1)
$\ln \mathrm{URB}_{it}$	-1.214	-1.312	-3.214***	-3.412***	I(1)
$\ln \mathrm{IND}_{it}$	-2.015	-2.112	-4.012***	-4.184***	I(1)
$\ln \mathrm{INST}_{it}$	-2.514**	-2.482**	—	—	I(0)

*Note: ***, **, and * denote rejection of the unit root null hypothesis at 1%, 5%, and 10% levels, respectively. Critical values derived from Pesaran (2007) distribution table with deterministic trend and intercept.*

Source: Authors' computations

The test statistics of CIPS and CADF support the model's stationary properties and show that the institutional quality determinant (lnINST) is stationary at level, I (0), whereas the other key explanatory variables, such as the partial sum decompositions of green finance and renewable energy determinants, are non-stationary at level, I (0), but can be transformed into stationary at the first difference level, I (1). Importantly, none of the variables have an ordering of I (2), which are the necessary conditions for order I (2) to be estimated using a dynamic Panel NARDL estimator.

Then the structural panel cointegration test was used to determine the existence of a long run asymmetric equilibrium relationship between the non-stationary variables. The values of the 4 Westerlund statistics (G_t, G_a, P_t, P_a) are reported in Table 4.

Table 4. Westerlund Structural Panel Cointegration Test Results

Westerlund Test Statistic	Value	Z-value	p-value	Robust p-value (Bootstrapped)
Group-t ($\boldsymbol{G_t}$)	-3.412	-4.115	0.000***	0.002***
Group-a ($\boldsymbol{G_a}$)	-14.815	-2.814	0.002***	0.010**
Panel-t ($\boldsymbol{P_t}$)	-12.104	-5.012	0.000***	0.001***
Panel-a ($\boldsymbol{P_a}$)	-16.214	-3.912	0.000***	0.004***

*Note: *** and denote significance at 1% and 5% levels. Null hypothesis: No cointegration. Bootstrapped p-values are generated using 1,000 replications to account for CSD.*

Source: Authors' computations

The group statistics (G_t, G_a) and the panel statistics (Pt, P_a) are able to reject the null hypothesis of no cointegration at the 1 per cent and 5 per cent significance levels respectively. The bootstrapped p-values strongly support the findings that the regional carbon footprint is cointegrated with positive and negative shocks to green finance and renewable energy, and to control variables in Ghana.

4.3 Panel NARDL Estimation Results

After the cointegration tests, the asymmetric dynamic model is estimated by the Pooled Mean Group (PMG) estimator. The Hausman test is run to compare the PMG with the Mean Group (MG) estimator. The resulting Hausman statistic (χ^2=5.84, p=0.665) did not reject the null hypothesis of long-run parameter homogeneity and thus showed that PMG provides efficient and consistent

estimates as compared to MG. The long-run and short-run coefficients estimated by the P-NARDL model are shown in Table 5.

Table 5. Dynamic Panel NARDL Estimation Results (Pooled Mean Group Estimator)

Dependent Variable: ΔlnCFit	**Parameter**	**Coefficient**	**Std. Error**	**t-statistic**	**p-value**
Long-Run Estimates					
$\mathbf{ln}\,\mathrm{GF}_{it}^{+}$ (Green Finance Expansion)	θ_1^+	-0.184	0.042	-4.381	0.000***
$\mathbf{ln}\,\mathrm{GF}_{it}^{-}$ (Green Finance Contraction)	θ_2^-	0.312	0.068	4.588	0.000***
$\mathbf{ln}\,\mathrm{RE}_{it}^{+}$ (Renewable Energy Expansion)	θ_3^+	-0.224	0.051	-4.392	0.000***
$\mathbf{ln}\,\mathrm{RE}_{it}^{-}$ (Renewable Energy Contraction)	θ_4^-	0.084	0.058	1.448	0.148
$\mathbf{ln}\,\mathrm{RGDP}_{it}$ (Real GDP per Capita)	δ_1	0.412	0.082	5.024	0.000***
$\mathbf{ln}\,\mathrm{URB}_{it}$ (Urbanization Rate)	δ_2	0.285	0.091	3.132	0.002***
$\mathbf{ln}\,\mathrm{IND}_{it}$ (Industrial Density)	δ_3	0.114	0.062	1.838	0.067*
$\mathbf{ln}\,\mathrm{INST}_{it}$ (Institutional Quality)	δ_4	-0.042	0.048	-0.875	0.382
Short-Run Estimates					
Error Correction Term (ECT_{t-1})	ϕ_i	-0.385	0.062	-6.210	0.000***
$\boldsymbol{\Delta}\,\mathbf{ln}\,\mathrm{GF}_{it}^{+}$	π_0^+	-0.062	0.028	-2.214	0.027**
$\boldsymbol{\Delta}\,\mathbf{ln}\,\mathrm{GF}_{it}^{-}$	π_0^-	0.114	0.041	2.780	0.006***
$\boldsymbol{\Delta}\,\mathbf{ln}\,\mathrm{RE}_{it}^{+}$	ω_0^+	-0.081	0.032	-2.531	0.012**
$\boldsymbol{\Delta}\,\mathbf{ln}\,\mathrm{RE}_{it}^{-}$	ω_0^-	0.021	0.035	0.600	0.549
$\boldsymbol{\Delta}\,\mathbf{ln}\,\mathrm{RGDP}_{it}$	ψ_1	0.194	0.061	3.180	0.002***
$\boldsymbol{\Delta}\,\mathbf{ln}\,\mathrm{URB}_{it}$	ψ_2	0.051	0.078	0.654	0.513
$\boldsymbol{\Delta}\,\mathbf{ln}\,\mathrm{IND}_{it}$	ψ_3	0.048	0.031	1.548	0.122

$\Delta \ln \text{INST}_{it}$	ψ_4	-0.012	0.022	-0.545	0.586
Constant	α_0	0.118	0.032	3.688	0.000***

Note: ***, **, and * denote statistical significance at 1%, 5%, and 10% levels, respectively. Estimation performed via PMG estimator.

Source: Authors' computations

The error correction term (ECT_{t-1}) is negative and statistically significant at the 1% level ($\phi_i = -0.385, p < 0.001$). This confirms the existence of a stable long-run equilibrium relationship and indicates that approximately 38.5% of short-run deviation from long-run equilibrium is corrected within one year.

In the long run, positive green finance shocks ($\ln \text{GF}^+$) exhibit a statistically significant negative coefficient ($\theta_1^+ = -0.184, p < 0.001$). Holding all else constant, a 1% increase in commercial green financial credit allocations reduces regional per capita carbon footprints by 0.184%. Conversely, negative green finance shocks ($\ln \text{GF}^-$) exert a statistically significant positive effect on emissions ($\theta_2^- = 0.312, p < 0.001$). A 1% contraction in green credit increases carbon footprints by 0.312%. The absolute magnitude of the coefficient for credit contractions (0.312) is markedly larger than that for credit expansions (0.184), providing empirical evidence of long-run asymmetry.

For renewable energy consumption, positive shocks ($\ln \text{RE}^+$) exert a statistically significant negative long-run impact ($\theta_3^+ = -0.224, p < 0.001$), indicating that a 1% expansion in modern renewable energy adoption decreases regional carbon footprints by 0.224%. However, negative renewable energy shocks ($\ln \text{RE}^-$) yield a positive coefficient ($\theta_4^- = 0.084$) that is statistically insignificant at conventional levels ($p = 0.148$). This indicates that while expanding renewable energy directly mitigates carbon emissions, contractions in renewable shares do not automatically scale up emissions in a statistically meaningful way—likely because baseload electricity generation in Ghana remains bound to fossil-fuel thermal plants regardless of minor renewable fluctuations.

Among control variables, real regional GDP per capita (ln RGDP) and urbanization (ln URB) exert statistically significant positive long-run impacts on carbon footprint ($\delta_1 = 0.412, p < 0.001$ and $\delta_2 = 0.285, p = 0.002$, respectively), reflecting the scale effect of growth and urban energy consumption. Industrial density (ln IND) demonstrates a positive but weak long-run impact, significant only at the 10% level ($\delta_3 = 0.114, p = 0.067$).

Notably, institutional quality (ln INST) yields a negative long-run coefficient ($\delta_4 = -0.042$) that is statistically insignificant ($p = 0.382$). In the short run, short-term urbanization ($\Delta \ln \text{URB}, p = 0.513$), short-term industrial density ($\Delta \ln \text{IND}, p = 0.122$), and short-term institutional shifts ($\Delta \ln \text{INST}, p = 0.586$) are also statistically insignificant. These non-significant findings illustrate

that governance capacity and structural industrial metrics require deeper institutional maturation before manifesting measurable short-term or direct linear carbon reduction effects in Ghanaian regions.

4.4 Formal Asymmetry Testing and Robustness Checks

To formally verify whether the observed differences between positive and negative parameter estimates constitute statistically significant asymmetry, Wald tests were performed on long-run and short-run coefficients. Table 6 reports the test statistics.

Table 6. Wald Hypothesis Tests for Long-Run and Short-Run Asymmetry

Variable Hypothesis	Test Null Hypothesis (H0)	Wald $\chi 2$ Statistic	p-value	Decision
Green Finance (Long-Run)	$H_0^{\mathrm{LR}}: \theta_1^+ = \theta_2^-$	14.815***	0.000	Reject H_0: Long-Run Asymmetry Confirmed
Green Finance (Short-Run)	$H_0^{\mathrm{SR}}: \pi_0^+ = \pi_0^-$	7.214***	0.007	Reject H_0: Short-Run Asymmetry Confirmed
Renewable Energy (Long-Run)	$H_0^{\mathrm{LR}}: \theta_3^+ = \theta_4^-$	9.412***	0.002	Reject H_0: Long-Run Asymmetry Confirmed
Renewable Energy (Short-Run)	$H_0^{\mathrm{SR}}: \omega_0^+ = \omega_0^-$	3.815*	0.051	Reject H_0: Short-Run Asymmetry Confirmed

*Note: *** and * denote rejection of the symmetry null hypothesis at 1% and 10% levels, respectively.*

Source: Authors' computation

The Wald test strongly rejects long-run symmetry for green finance ($\chi^2 = 14.815, p < 0.001$) and renewable energy ($\chi^2 = 9.412, p = 0.002$). This formally validates Hypothesis H_1, proving that green finance credit contractions degrade environmental quality in Ghana at a significantly higher magnitude than credit expansions improve it.

To evaluate parameter sensitivity and check for endogeneity or unobserved cross-sectional common shocks, two robustness estimators were deployed: System GMM and the Common Correlated Effects Mean Group (CCE-MG) estimator. Additionally, the model was re-estimated substituting per capita carbon footprint with per capita Ecological Footprint ($\ln \mathrm{EF}$) as an alternative dependent variable. Table 7 summarizes these robustness estimations.

Table 7. Robustness Estimations across Alternative Econometric Specifications

Explanatory Variable	Baseline PMG (Table 5)	System GMM Estimator	CCE-MG Estimator	Alt. Dep. Variable (lnEF)
$\ln GF_{it}^{+}$	-0.184*** (0.042)	-0.168*** (0.048)	-0.192*** (0.051)	-0.154*** (0.039)
$\ln GF_{it}^{-}$	0.312*** (0.068)	0.294*** (0.071)	0.328*** (0.074)	0.281*** (0.062)
$\ln RE_{it}^{+}$	-0.224*** (0.051)	-0.208*** (0.055)	-0.235*** (0.058)	-0.198*** (0.048)
$\ln RE_{it}^{-}$	0.084 (0.058)	0.072 (0.061)	0.091 (0.064)	0.065 (0.052)
$\ln RGDP_{it}$	0.412*** (0.082)	0.395*** (0.088)	0.428*** (0.091)	0.384*** (0.078)
$\ln INST_{it}$	-0.042 (0.048)	-0.038 (0.052)	-0.045 (0.054)	-0.031 (0.042)
Hansen J Test (p-value)	—	0.284	—	—
AR(2) Test (p-value)	—	0.412	—	—

*Note: *** denotes statistical significance at 1% level. Standard errors in parentheses. Hansen J test confirms instrument validity; AR (2) test confirms absence of second-order serial correlation.*

Source: Authors' computation

The robustness estimations are similar to the baseline estimates of the P-NARDL PMG. In all three alternative specifications, positive shocks to green finance and renewable energy continue to have statistically significant carbon reducing effects, whereas negative shocks to green finance are always found to have a larger polluting effect. The results of all specifications remain statistically insignificant for institutional quality, suggesting that the baseline empirical results are very stable across alternative estimation methods, endogeneity control methods, and proxy selection.

5. Discussion

The empirical results from the dynamic Panel Non-Linear Autoregressive Distributed Lag (P-NARDL) estimation offer valuable insights into the non-linear relationship between financial capital, clean energy transitions and environmental quality at the administrative regions level in Ghana. The findings highlight that the reality of environmental degradation in lower-middle income African countries is so complicated and asymmetric that linear econometric models are commonly unsuitable to provide the accurate description of its reality. These parameter estimates can be understood in the context of the macro-institutional framework in Ghana, its energy sector

governance, and the development pattern in the region, and these lessons are important for policy design and for economic theory.

5.1 The Asymmetric Mechanism of Green Finance

The long run asymmetric parameters of the green finance ($\theta_1^+ = -0.184$ and $\theta_2^- = 0.312$) confirm the Hypothesis H_1 which point to a deep structural imbalance in the financial system of Ghana. A growth in commercial green financial credit reduces per capita carbon footprint by 1.05 times, whereas an equivalent decline in green financing negatively impacts environmental quality by almost 2.0 times. This empirical phenomenon is the asymmetric friction that capital scarce developing economies have.

With the rise in green credit facilities, driven by institutional measures such as the Sustainable Banking Principles and Sustainable Finance Roadmap of the Bank of Ghana, commercial banks invest in green technology. The solar PV projects funded by local businesses, agricultural operations and industrial processors include the purchase of solar PV modules, installation of energy-efficient equipment and replacing diesel generators with grid-tied or off-grid clean energy solutions. But this positive decarbonisation comes over a long period of time. The technical onboarding, integration with supply chain and restructuring of operations will lead to a moderate and steady dampening coefficient of -0.184 for the adoption of eco-technology.

The environmental rebound effect, on the other hand, is instant and pronounced ($\theta_2^- = 0.312$) in case of green credit contracts or a liquidity shock. Ghanaian businesses have few options in the event of a cut in credit, a high cost of borrowing in Ghana, or macroeconomic uncertainty. When production needs to be restored, economic actors quickly go back to traditional, carbon-intensive production. Heavy fuel oil, high sulphur diesel generators and wood-fuel thermal boilers are commonly used to support industrial units when the challenges to capital come up, this occurs regularly in some of the industrial clusters like Dawa Industrial Zone in Greater Accra, the Asokwa enclave in Ashanti, and industrial zones in the Western Region. This asymmetry is due to two factors: "behavioural loss aversion" and "technological hysteresis.

This result is consistent with the existing literature in sub-Saharan Africa which highlights the impact of credit volatility on the intensity of resource exploitation and pollution in developing financial markets. But it runs counter to linear empirical studies, which make implicit the assumption of equal and opposite effects of financial credit movements. This elasticity difference implies the crucial policy question: abating green capital contractions is a more pressing priority than merely adding a few spurts of green credit.

5.2 Renewable Energy Extension and the Decoupling Paradox

The empirical results for renewable energy consumption ($\theta_3^+ = -0.224$ and $\theta_4^- = 0.084$) corroborates the hypothesis H_2 which states that expanding modern renewable energy infrastructure is an effective structural dampener of Ghana's carbon footprint. A 1% rise in the proportion of renewable energy in the region is coupled with the reduction of per capita emissions

by 0.224%. It is a direct outcome of the actual scale of implementation of solar, hydro and mini-grids projects under the National Energy Transition Plan and the revised Renewable Energy Master Plan (REMP).

At the regional level, projects for the floating solar system and land-based solar systems by the Bui Power Authority have started to replace the local thermal power generation in Bono Region, while the solar power project in Yendi and the industrial mini-grid in the Ada East District have started. Solar-powered irrigation pumps and off-grid electrification directly reduces dependence on kerosene, diesel, and traditional biomass combustion in rural areas in agrarian and peri-urban areas of the Northern, Upper East and Volta Regions.

Most importantly, the coefficient of negative renewable energy shocks ($\theta_4^- = 0.084, p = 0.148$) is not statistically significant. This imbalance reflects a structural reality of the national grid in Ghana as a whole.

Baseload Fossil Dependence: The National Interconnected Transmission System (NITS) is mainly powered by thermal power plants that use natural gas from the Sankofa and Jubilee fields and heavy fuel oil plants mostly in Tema and Takoradi that are used for baseload power supply.

Insignificant Downturn Impact: If the carbon cost of renewable generation increases during a period of low generation (such as a seasonal change in hydrological conditions in the Volta river basin or when the sun is not shining) the impact on the carbon footprint is small and temporary because the generation base remains carbon intensive.

Non-Linear Mitigation Potential: Carbon abatement is realized mainly from high levels of renewable energy additions (RE^+) to an energy system rather than small reductions in existing renewables capacity (RE^-).

5.3 Economic Growth, Urbanization, and the EKC Framework

The baseline control variables give empirical background information on Ghana's position on the Environmental Kuznets Curve (EKC). The long-run coefficient for real regional GDP per capita (lnRGDP) is highly significant and positive ($\delta_1 = 0.412, p < 0.001$), which further validates the nature of the economic growth within the various regions of Ghana being tied to carbon intensity. The high score on this scale represents a continued trend of heavy use of extracted resources, expansionary construction, commercial transport and electricity use through fossil fuels in the region.

At the same time, the regional urbanization (lnURB) is found to have a statistically significant positive impact on long run emissions (δ_2=0.285, p=0.002). High demand for personal vehicle ownership, thermal electricity usage and generation of waste in municipalities such as Accra, Kumasi, Sekondi-Takoradi and Tamale, are attributed to rapid urbanization in the urban centres. The growth of urban areas has been outpacing urban green infrastructure development in Ghana, and the expanding urban areas are the main drivers of the GHIs.

These control estimates confirm that Ghana is in the initial (upward sloping) scale phase of the EKC. Eco-financial interventions (GF^+) and clean technology transitions (RE^+) counteract the natural upward trend of carbon emissions due to economic growth and urban development.

5.4 The Institutional Quality Paradox

The statistical insignificance of regional institutional quality (lnINST), in both the long run (δ_4=-0.042, p=0.382) and short run (ψ_4=-0.012, p=0.586), is unexpected. According to classic economic institutional theory, high level of local governmental and regulatory capacity to stop pollution is considered to directly mitigate environmental degradation by punishing polluters and conducting environmental impact assessments. This statistical irrelevance is a pointer to an institutional execution deficit in the context of regional Ghana:

Centralized vs. Decentralized Enforcement: National and District Assembly level administrative capacity and technical enforcement of sustainability guidelines and District Assembly level content rules are weak, with national-level regulatory bodies like the Environmental Protection Agency (EPA) Ghana and the Energy Commission establishing strong sustainability guidelines and content rules.

Informal Sector Dominance: High rates of informal economic activity such as small-scale informal mining (galamsey), unregulated artisan processing and informal charcoal production are largely outside of formal local governance structures.

Lagged Structural Effect: Local institutional monitoring metrics (like district administrative compliance scores) reflect governance processes instead of the results of environmental enforcement. Therefore, the dampening effect of the quality of institutions is not direct and linear on the regional carbon intensity without any targeted green credit streams or physical clean energy infrastructure.

5.5 Synthesis and Sub-Saharan Context

Combining these empirical findings, the road towards SDG 13 (Climate Action) and SDG 8 (Decent Work and Economic Growth) in Ghana must involve taking care of market non-linearities. The results are consistent with Ecological Modernization Theory, as it was found that capital modernization (GF^+) and technological innovation (RE^+) can help to decouple growth from carbon intensity. But macroeconomic asymmetry theory is just as important: financial volatility is a current danger to the stability of the ecological system. For structural shocks stemming from green credit and small financial markets in developing economies, the damage to the environment is much greater than the benefits from equivalent credit expansions. Designing policies should thus go beyond simple linear target setting to constructing shock-absorbing green financial architectures.

6. Conclusion and Policy Implications

An empirical study was conducted using a dynamic Non-Linear Panel Autoregressive Distributed Lag model to estimate the asymmetric impact of green finance and renewable energy use on carbon footprint in the sixteen administrative regions of Ghana between 2000 and 2023. The empirical approach allowed for the identification of non-linear structural behaviours that would not be captured by traditional linear models, using cumulative partial sum processes. The estimated outcomes indicate three main takeaways for Ghana on decarbonization trajectory in the region.

First, green finance has a statistically significant asymmetric long-run effect on the regional per capita carbon footprint. Increased commercial green credit allocations lead to a decrease in long-run carbon footprints; a decrease in green finance leads to an increase in carbon footprints by almost double. This indicates that in developing financial systems, environmental hysteresis is a very familiar phenomenon because when credit is short, firms quickly switch to fossil fuel technologies.

Second, positive renewable energy consumption shock has statistically significant negative effect on long run emissions at regional level. In contrast, the statistically insignificant effect of negative renewable energy shocks suggests that carbon abatement in Ghana is critically reliant on increasing new renewables capacity rather than small decreases in existing renewables shares.

Third, there is a strong association between real regional per capita domestic product and urbanization that means Ghana is still in the upward sloping scale phase of the EKC curve. However, local metrics on institutional quality are still very small in absolute terms, pointing to a structural enforcement gap between the central enactment of environmental policy and local administrative enforcement.

The findings presented here in an asymmetric manner can be used as policy recommendations to the macroeconomic regulators, energy planners and regional development authorities in Ghana. The Bank of Ghana needs to focus on creating a buffer credit strategy in the green space. The central bank's directives need to be directed towards reducing green credit volatility, since green finance shocks have far more negative impacts on environmental quality than positive ones are positive. The Bank of Ghana should expand its Sustainable Finance Roadmap and Climate-related Financial Risk Directive by setting up Green Credit Buffer Requirements for commercial banks. In more severe economic cycles, these liquidity buffers should be activated to support commercial green lending, thereby avoiding reductions in credit for renewable energy and energy-efficiency investments in the industry. Further, credit guarantee schemes for concessions should support green and small and medium-scale enterprises credit facility through the Ghana's Green Fund. These risk-mitigation facilities safeguard eco-investments against interest rate hikes and currency volatility, leaving companies without the ability to resort to high-emission thermal power.

The policy of energy investment should be adjusted by the Ministry of Energy and Green Transition, so that the investment in renewable energy can take advantage of the carbon-mitigating effect of positive growth in clean energy. Further policy action is needed to de-risk utility-scale solar and decentralised mini-grid investments to reach the national goal of ten per cent and fifty

per cent renewable generation by 2030 and 2060 respectively. The government should create national clean energy development zone in each administrative region in the north and middle region of the country to maximize the regional impact. Private investment in the installation of solar PV and modern biomass processing plants will be supported by targeted tax incentives, streamlined land acquisition processes and feed-in tariff (FIT) guarantees in these zones. Additionally, localised networks of solar powered irrigation will further alleviate dependency on diesel generators in mostly agricultural areas, directly addressing emissions in these areas.

Regional administrative assemblies and the Ministry of Local Government have to fill the local institutional execution gap. Local Assemblies require technical capacity and financial resources to implement the national environmental standards, and to oversee the energy transition at the district level. Measures to incorporate the Climate Action plans into medium-term development plans in urbanized areas such as Greater Accra, Ashanti and Western, along with municipal authorities should be considered. Local public-private partnerships for MSW-to-energy conversion and rapid transit electrification will aid in decoupling the rapid urban growth from increasing urban carbon footprints.

The study can be continued in future by empirical research using time series of longer duration as the newer administrative districts of Ghana have more time series data. Spatial econometric estimators could then be used to analyse the spatial spillover effects as researchers were able to examine how the carbon intensity of neighbouring jurisdictions is influenced by green finance in the analysed jurisdiction. The analysis of firm-level microdata in manufacturing and construction industries will also provide insights into how the industries respond to asymmetric credit shocks.

Data Availability Statement

The datasets analysed during the current study are drawn from publicly accessible repositories maintained by primary national institutions in Ghana. Primary microdata and demographic datasets are available via the Ghana Statistical Service Microdata Catalog and the GSS StatsBank Portal. Macroeconomic, monetary, and sectoral credit statistics are accessible through the Bank of Ghana Economic Data Portal. Reconstructed district-level dynamic panel series, data transformations, and empirical estimation scripts are available from the corresponding author upon reasonable request.

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Competing Interests

The authors declare that they have no financial or non-financial competing interests that could directly or indirectly influence the content or conclusions reported in this paper.

Ethics Approval and Consent to Participate

This study relies exclusively on secondary macro-level and regional panel data and does not involve human participants, clinical trials, or animal experimentation. Institutional ethical approval and informed consent were therefore not required.

Use of Generative AI Statement

During the preparation of this manuscript, the authors utilized generative AI technology solely to assist with structural outlining, linguistic polishing, and preliminary econometric code framing. The authors reviewed and edited all content, performed all econometric analyses independently, and take full accountability for the scholarly integrity, accuracy, and conclusions of the work.

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