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**Green finance, energy transition, and carbon intensity in Africa: unpacking the finance–
energy-carbon nexus**

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

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**All authors contributed to the study conception and design. Material preparation, data
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Abstract

This study analyses the interconnected relationship between green finance, energy transition, and carbon intensity in Africa. Using a panel of 35 African countries over the period 2000-2023, this study employs fixed effects, Driscoll-Kraay standard errors regression, and two-stage least squares instrumental variables to examine the effects of clean energy finance on wind, solar, and hydropower generation, the implications of the resulting energy mix for carbon intensity, and the potential feedback effect of renewable energy development on climate finance. The results show that clean energy finance has a positive and robust effect on wind and solar generation but a negative and robust effect on hydropower, indicating a technology-specific rather than uniform effect. However, sub-regional analysis reveals that green finance-renewable energy relationship is far from uniform across the continent. Clean energy finance also contributes to lower significantly carbon intensity, operating partly through this renewable-generation channel, although persistent coal- and oil-rent dependence continues to sustain emissions intensity in several economies. The strong and consistent role of climate resilience/readiness in promoting renewable energy and thereby reducing carbon emissions suggests that investments in institutional and adaptive readiness are not merely a co-benefit of climate policy but a structural precondition for energy transition and the effective absorption of green finance. A reverse-causality test further finds that countries with more established wind and solar

60 capacity attract significantly more clean energy finance. These findings indicate that the
61 effectiveness of green finance depends on institutional readiness, existing energy infrastructure,
62 and regional context, and call for redirecting climate finance toward vulnerable countries and
63 scalable renewable technologies within next-generation NDCs.

64 **Keywords:** Green finance; Energy transition; Renewable energy; Carbon intensity; Africa;
65 Panel data

1. Introduction

Climate change mitigation depends fundamentally on the pace at which the global energy system moves away from fossil fuels toward a low-carbon energy system (Amoah et al. 2025; Naeem et al. 2023; Nepal et al. 2024). The energy sector remains the single largest source of anthropogenic greenhouse gas (GHG) emissions, driven overwhelmingly by continued reliance on fossil fuels for electricity generation, transport, and industrial activity (World Bank 2022; IEA 2025). Since the Paris Agreement of 2015, accelerating the transition toward a low-carbon energy system has become a central pillar of global climate policy. The international community has treated the decarbonization of energy systems as a critical pathway to limiting global warming, a priority formalized under Sustainable Development Goals (SDG) 7 (affordable and clean energy) and 13 (climate action) (IRENA 2024). Within this global effort, Africa occupies a distinctive and consequential position. The continent bears negligible historical responsibility for cumulative GHG emissions, yet it is disproportionately exposed to the physical impacts of climate change, which compound the continent's already limited adaptive capacity. At the same time, Africa possesses substantial renewable-energy endowments, positioning it as a potentially pivotal, if underutilized, contributor to global mitigation efforts should this potential be harnessed rather than bypassed in favor of continued fossil-fuel dependence.

This climate imperative is tightly attached to the pressing development imperative of Africa. More than 600 million Africans currently lack access to electricity, meaning the continent must expand energy production substantially over the coming decades regardless of source (IEA 2022; OECD 2022). The way in which this expansion occurs, whether it locks in new fossil-fuel infrastructure or is built around low-carbon alternatives, will shape both Africa's future emissions trajectory and the credibility of the global transition as a whole, given that infrastructure decisions made today will constrain energy systems, and their associated emissions, for decades to come. Fortunately, Africa is not resource-constrained in this aspect: the continent holds some of the highest levels of solar irradiation in the world, alongside substantial hydropower and considerable wind potential (IEA 2022; IRENA 2023). However, high financing costs and external shocks, limited access to capital, and institutional and regulatory barriers continue to constrain the development of bankable clean energy projects (Ali and Adjai 2023; IEA 2023).

Green finance, defined as the set of public and private financial flows directed toward low-carbon and climate-resilient investments (Fu et al. 2023), is widely recognized as critical enabler for over-coming these challenges and unlocking Africa's renewable energy potential. Theoretically, the energy-ladder theory suggests that rising income and financial capacity may progressively facilitate a transition toward cleaner energy sources, while targeted green-finance mechanisms can potentially accelerate this transition by easing financial constraints and supporting investments in renewable energy technologies (Hosier and Dowd 1987; Leach 1992). This theory provides the foundations for understanding the energy transition, which refers to the process of shifting from high-carbon to low-carbon energy resources and from low to high energy efficiency (Chishti et al. 2023). This transition requires substantial financial support, and traditional financial theory suggests that financial development can foster the

necessary economic conditions by promoting capital accumulation, improving capital allocation, and strengthening risk management (Levine 2005).

However, the energy-ladder theory has been challenged by the energy-stacking theory, which argues that households and economies do not simply abandon traditional fuels as income and development levels rise. Instead, they stack multiple energy sources, combining modern and traditional energy sources, with the composition of their energy portfolios shaped by affordability, reliability, accessibility, and socioeconomic context (Masera et al. 2000). This perspective implies that green finance does not automatically lead to the displacement of carbon-intensive energy, rather it reshapes the composition of the energy mix, enabling cleaner sources to be added alongside, and gradually substitute, existing ones. Consequently, the effectiveness of green finance in driving the energy transition depends not only on the volume of financial flows but also on their allocation, design, and capacity to support a sustained shift away from carbon-intensive energy systems.

Empirically, financial development contributes to the energy transition through three distinct channels (Lee et al. 2024). The first and most evident is the technology innovation effect, as numerous studies have confirmed that technological progress reduces energy intensity and improves energy utilization efficiency (Lee et al. 2023; Zhao et al. 2022). The second channel is the resource allocation effect; whereby green finance optimizes the allocation of financial resources to support an equitable energy transition. On the production side, financial development can facilitate the allocation of capital toward firms adopting green management practices and investing in environmentally sustainable technologies, while strengthening incentives to reduce financing for carbon-intensive activities and fossil fuel dependence (Lee and Lee 2022). On the consumption side, green finance can encourage consumers to adopt less energy-intensive products, promote non-fossil energy use, and enhance their capacity to transition toward cleaner energy through financial instruments such as grants, low-interest loans, and preferential credit facilities (Michelsen and Madlener 2016). The third channel is the capital support effect, which points to the importance of proper and adequate financing for clean energy infrastructure projects given their large initial investment requirements and long implementation cycles (Li et al. 2023).

Against this background, three research gaps limit our understanding of how green finance shapes Africa's contribution to the global climate effort. First, although green finance is theoretically expected to catalyze energy transition and contribute to emissions reduction, its overall effect on renewable energy deployment in Africa remains empirically ambiguous, with existing studies reporting mixed results depending on the type of financial instrument and methodological approach used (Belgacem et al. 2023; Mugume and Bulime 2024; Nepal et al. 2024). Second, whether the ongoing energy transition translates into meaningful reductions in macroeconomic carbon intensity across African economies remains insufficiently established. This uncertainty is particularly relevant in the context of energy stacking, where renewable energy expansion may coexist with continued reliance on carbon-intensive energy sources, potentially limiting the extent to which changes in the energy mix translate into measurable climate benefits. Third, the potential reverse causality between green finance and energy transition has received limited attention. It remains unclear whether green finance accelerates

the energy and carbon transition, or whether countries already advancing in renewable energy deployment may themselves attract greater green investment. Beyond these questions, the role of institutional and climate readiness in shaping the flow of green finance requires further analysis, in order to determine which countries are positioned to successfully attract and absorb green investment, and which risk being left behind in the global reallocation of green capital (Climate Policy Initiative 2021). The objective of this study is therefore to examine the interconnected relationship between green finance, energy transition, and carbon emissions in Africa, with a view to informing both national energy policy and the broader international green-finance architecture. Specifically, it aims to (i) assess the effect of green finance on renewable energy, and (ii) evaluate the impact of this energy transition on carbon intensity. By simultaneously testing the reversibility of these relationships, addressing endogeneity, and conducting disaggregated analyses by sub-region, this study advances the empirical literature on the energy-finance-climate nexus and provides evidence directly relevant to the design of green-finance instruments intended to accelerate mitigation in the world's most climate-vulnerable region.

This study builds on existing research on the energy-finance-emissions nexus by offering new evidence tailored to the African context. Prior work has generally examined either the effect of financial development on renewable-energy adoption (Belgacem et al. 2023; Nepal et al. 2024) or the environmental consequences of renewable-energy deployment (Bhattacharya et al. 2017; Mirziyoyeva and Salahodjaev 2022; Naeem et al. 2023), typically treating the finance-transition-emissions chain as unidirectional. This study instead brings these two dimensions together within a single empirical framework, jointly examining whether green finance promotes a higher renewable-energy share and whether the resulting changes in the energy mix subsequently translate into lower carbon intensity.

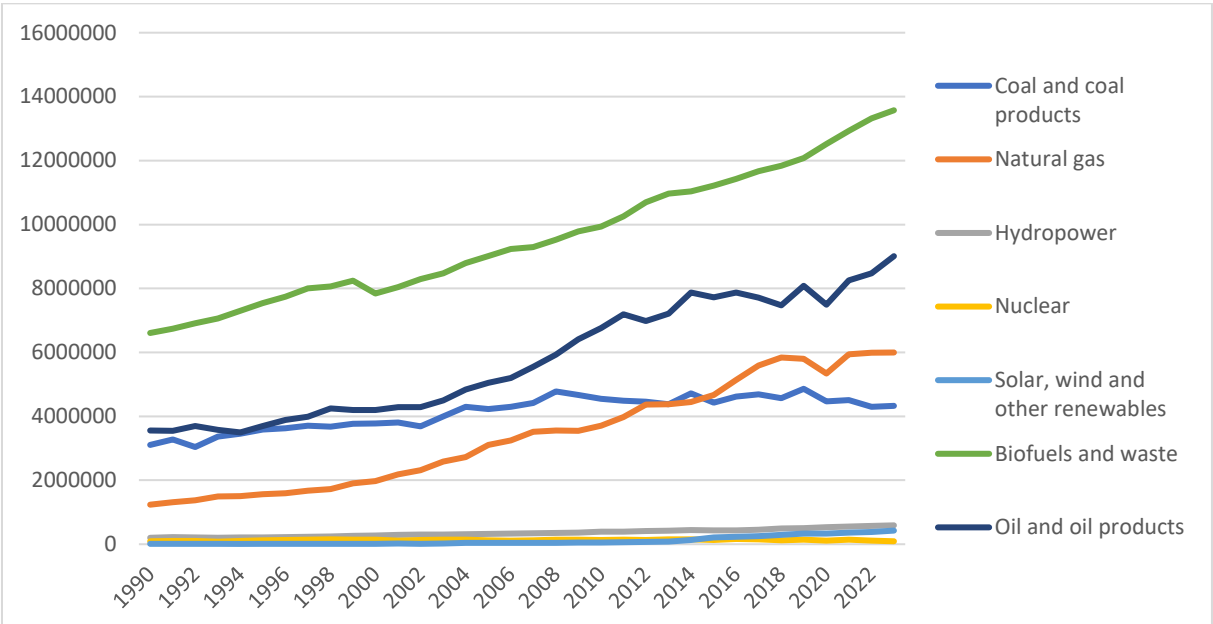
The remainder of the paper is structured as follows. Section 2 presents stylized facts on green finance and the energy mix in Africa; Section 3 reviews the relevant literature; Section 4 presents the methodology and data; Section 5 discusses the empirical results; and Section 6 concludes with policy implications for climate finance and energy-transition policy.

2. Stylized facts

Africa faces persistent challenges in transitioning to low-carbon energy despite its abundant renewable energy resources. The continent possesses substantial renewable energy potential, accounting for approximately 60% of the world's best solar resources while representing only 1% of global installed solar PV capacity (IEA 2022). Despite this substantial resource endowment, renewable energy deployment remains limited relative to global expansion. Africa added 4.7 GW of renewable power capacity in 2024, compared with 582 GW globally (IRENA 2025). This gap suggests that resource availability alone is insufficient; financial, infrastructural, and institutional constraints remain the binding limits on the pace of Africa's energy transition. From 1990 to 2023, energy expansion has largely occurred through continued reliance on biofuels and waste and the growing use of fossil fuels, while modern renewable sources (solar, wind, and other renewables) remain relatively limited. The share of solar, wind, and other renewable energy sources in the total energy supply is around 1%, while the share of fossil fuels is over 57% in 2023 (Figure 1).

In 2022, total energy investment in Africa was below USD 90 billion, while clean energy investment amounted to around USD 25 billion, representing approximately 2% of global clean energy investment (IEA 2023). Expanding renewable energy alongside growing energy demand could help meet Africa’s development needs while limiting future carbon emissions and reducing the continent’s contribution to climate change. This makes green finance particularly important for steering Africa’s rapidly expanding energy system toward a low-carbon and climate-resilient pathway.

Figure 1: Evolution of total energy supply in Terajoule (TJ)



Source: Authors using IEA data (2025).

3. Literature review

Two theoretical traditions established the relationship between green finance, energy transition, and carbon emissions. The first, finance-growth-environment literature, builds on the finance-growth nexus (King and Levine 1993; Levine 2005) and points the role of financial development in allocating capital toward productive and environmentally sustainable investments, including low-carbon technologies (Fu et al. 2023). The second builds on energy-transition theory, encompassing the energy-ladder (Hosier and Dowd 1987; Leach 1992) and energy-stacking (Masera et al. 2000) perspectives, which explain how rising income, technological capacity, and contextual constraints shape the shift toward cleaner energy sources. While the energy-ladder theory emphasizes progressive fuel substitution, the energy-stacking perspective reveals the coexistence of traditional and modern energy sources, suggesting that green finance may gradually reshape the energy mix rather than immediately displace carbon-intensive fuels.

A growing literature indicates that green finance supports energy transition and reduces carbon emissions, although findings vary across contexts and methods. In advanced economies, evidence is relatively consistent. Alvi et al (2025), using FMOLS, FGLS, and MMQR on 31 OECD countries (2000-2020), show that green finance significantly reduces GHG emissions

by supporting renewable energy development, environmental innovation, and energy transition, with digitization and environmental taxes reinforcing these benefits. Sinha et al. (2023) and Lei et al. (2024) confirm the environmental benefits of green finance in OECD economies, while Liu et al. (2023), applying a CS-ARDL model to G7 countries (2000-2020), document significant long-run contributions of financial development and renewable investment to sustainable energy transitions. In emerging economies, Lee et al. (2024) document, using provincial Chinese data with dynamic threshold effects, that green finance development accelerates energy transition, but the effect is moderated by climate risk. Liu et al. (2022) demonstrate that green credit significantly encourages low-carbon technological innovation, especially in regions that are already making progress in their clean energy transitions.

For developing economies, the literature emphasizes both the potential of green finance and the structural constraints that limit its effectiveness. Ali and Adji (2023) highlight how external shocks, such as the Russia-Ukraine war, have exposed Africa's energy security vulnerabilities, arguing that African policymakers should rethink food and energy sovereignty policies to resist future external shocks. This context is important for understanding why green finance alone may be insufficient without complementary structural reforms. Nepal et al. (2024), using IV-2SLS on 32 countries (2003-2020), find that each additional million dollars of international green finance generates on average 88 GWh of additional renewable energy consumption, with particularly strong effects for hydropower and wind. Belgacem et al. (2023) confirm that green bonds encourage long-term renewable energy investments in emerging Asian economies. In Africa specifically, evidence is notably mixed. Amoah et al. (2025), using a PVAR-GMM model on 36 SSA countries (2000-2022), find that past renewable transitions positively influence current green finance receipts, but green finance flows do not significantly drive energy transition. Mugume and Bulime (2024), studying 20 low- and middle-income SSA countries and employing fixed-effects and IV-2SLS, show that financial development promotes renewable energy adoption. Appiah et al. (2023), using Panel Quantile Autoregressive Distributed Lag (PQARDL), find that financial development and fiscal policy negatively affect renewable energy across all quantile distributions in the long run.

4. Methodology and Data

4.1. Theoretical Framework and Empirical Strategy

4.1.1. Theoretical background

The empirical strategy adopted in this study is based on the finance-growth-environment framework (King and Levine 1993). In this context, financial flows influence the technologies adopted by shaping investment conditions. By reducing financing costs, sharing risks, and enhancing the bankability of capital-intensive projects, green finance can facilitate the deployment of renewable energy technologies that might otherwise remain financially unviable (Polzin and Sanders 2020). This provides the theoretical rationale for treating international clean energy finance as a determinant of renewable electricity generation, and for expecting improvement in carbon efficiency.

Building on recent empirical contributions (Alvi et al. 2025; Amoah et al. 2025; Lee et al. 2024; Nepal et al. 2024), the energy transition equation is specified as:

$$ET_{it} = f(GF_{it}, INST_{it}, ECON_{it}) \quad (1)$$

where ET_{it} denotes energy transition indicators (hydropower, solar, and wind electricity generation per capita), GF_{it} captures green finance variables, $INST_{it}$ reflects institutional capacity (proxied by the ND-GAIN index), and $ECON_{it}$ includes macroeconomic factors such as GDP per capita, industry value added, foreign direct investment, etc.

Beyond its effect on energy transition, green finance is expected to play a central role in reducing carbon emissions. As investment in clean energy increases, dependence on carbon-intensive sources must decline, leading to lower carbon emissions (Ben Abdallah 2025). Similarly, as the share of renewable energy increases, dependence on fossil fuels declines, leading to lower carbon emissions (Naeem et al. 2023). Accordingly, carbon emissions can be expressed as:

$$CE_{it} = f(GF_{it}, ET_{it}, INST_{it}, ECON_{it}) \quad (2)$$

where CE_{it} represents carbon emission, measured by the annual emissions of CO₂, from the agriculture, energy, waste, and industrial sectors, divided by GDP

In addition to these relationships, the analysis considers the potential reverse channel linking the energy structure to green finance. From a theoretical standpoint, the signaling literature in green finance shows that countries already engaged in renewable energy deployment or exhibiting stronger climate performance may attract greater climate finance due to higher readiness, lower investment risk, and stronger policy credibility (Bhuiyan et al. 2025; Iorember and Yusoff 2023). In contrast, more carbon-intensive economies may face constraints in accessing green finance due to higher transition risks and weaker institutional frameworks (Kiremu et al. 2022). This suggests that green finance allocation may depend not only on environmental need but also on existing energy structures and institutional conditions. This relationship can be expressed as:

$$GF_{it} = f(ET_{it}, Fos_{it}, INST_{it}, ECON_{it}) \quad (3)$$

where Fos_{it} denotes fossil-fuel energy generation.

4.1.2. Empirical strategy

To empirically assess the relationships between green finance, energy transition, and carbon emissions, this study adopts a multi-step estimation strategy designed to address key econometric challenges inherent in panel data, including unobserved heterogeneity, heteroskedasticity, autocorrelation, cross-sectional dependence, and endogeneity. Following Mirziyoyeva and Salahodjaev (2022), Mugume and Bulime (2024), and Nepal et al. (2024), the baseline estimations are conducted using a panel fixed-effects (FE) model controlling for country- and time-specific effects. However, FE does not fully account for heteroskedasticity, autocorrelation, and cross-sectional dependence, which are particularly relevant in the context of global green finance flows and interconnected energy markets. To overcome these limitations, Driscoll-Kraay standard errors are adopted as the preferred estimator. This estimator is robust to heteroskedasticity, autocorrelation, and cross-sectional dependence

simultaneously (Driscoll and Kraay, 1998; Hoechle 2007), without requiring the number of cross-sectional units to be small relative to the time dimension.

Beyond the issue of correct inference, the relationship between clean energy finance and renewable-energy development is potentially subject to omitted-variable and simultaneity bias. While green finance may drive energy transition, countries already advancing in renewable energy deployment may themselves attract greater green investment, consistent with the signaling mechanisms described above (Zhong et al. 2024). To address these concerns, a two-stage least squares instrumental variable (2SLS-IV) approach is used. Public investment in renewable energy and the one-period lag of clean energy finance are used as instruments. Their validity rests on the relevance and exogeneity (exclusion restriction) conditions. Both instruments are strongly correlated with the endogenous regressor. Public investment from governments and development finance institutions constitutes a substantial share of recorded international green finance and is well documented in the literature as playing a catalytic role. Public capital is frequently deployed specifically to de-risk projects and crowd in additional private and blended finance, meaning that movements in public investment are closely associated with movements in the broader pool of clean energy finance a country receives (Polzin and Sanders 2020). The lagged value of clean energy finance is relevant by construction, given the well-documented persistence of donor-recipient financing relationships, multi-year project cycles, and programmatic climate-finance commitments, which imply strong serial correlation in a country's financing receipts over time. This relevance should be confirmed empirically by the Kleibergen-Paap rk Wald F-statistic, which must exceed the Stock-Yogo 10% maximal IV size critical value, and by the Kleibergen-Paap rk LM statistic, which must reject the null of under-identification.

Regarding the exogeneity condition, public investment decisions by donor governments and multilateral development finance institutions are shaped primarily by donor-country fiscal cycles, multilateral burden-sharing formulas, and global climate-policy commitments rather than by the contemporaneous, country-specific renewable-generation shocks captured in the error term. Moreover, country and year fixed effects further absorb any time-invariant country characteristics and common global shocks that might otherwise confound this exclusion restriction. The use of the lagged value of clean energy finance as an instrument follows the logic formalized by Reed (2015), who displays that instead of simply replacing a suspected endogenous regressor with its own lag to resolve simultaneity bias, an alternative is to use the lagged values as instruments in 2SLS-IV estimation. The two conditions proposed by Reed (2015) for using the lagged value as an instrument are valid in our study provided that (i) the lag does not itself belong in the second-stage equation, and (ii) it is sufficiently correlated with the current, endogenous regressor.

4.2. Data source

The study uses a panel dataset covering 35 African countries over the period 2000-2023. The selection of countries and timeframe is guided by data availability and consistency across all key variables, particularly green finance and energy variables. Table 1 presents the definitions and sources of all variables used in the empirical analysis.

339 **Table 1: Description of the Variables**

Variables	Description	Unit	Sources
Clean energy finance	Total international financial flows dedicated to clean energy projects in a given country and year	constant 2021 USD	Our World in Data (2026)
Public Investments	Financial flows from public sources (governments, development finance institutions, etc.) into renewable energy	million USD at 2022 prices and exchange rates	OECD-DAC (2024), IRENA (2025)
Fossil per capita	Electricity generation from fossil fuels per person measured in kilowatt-hours per person.	kWh per capita	Our World in Data (2026)
Hydro per capita	Per capita electricity generation from hydropower	kWh per capita	Our World in Data (2026)
Solar per capita	Electricity generation from solar power per person	kWh per capita	Our World in Data (2026)
Wind per capita	Electricity generation from wind power per person	kWh per capita	Our World in Data (2026)
Carbon intensity	Annual emissions of CO ₂ , from the agriculture, energy, waste, and industrial sectors, excluding LULUCF divided by the GDP in constant 2021 US\$.	kg CO ₂ e/2021 USD of GDP	World Bank (WDI)
ND-GAIN index	Composite index measures a country's vulnerability and readiness to adapt to climate change.	-	Notre Dame Global Adaptation Initiative
GDP per capita	Gross domestic product per capita measured in	Current USD	World Bank (WDI)
Foreign direct investment	Foreign direct investment net inflow in percentage of GDP	%	World Bank (WDI)
Coal rents	Coal rents in percentage of GDP	%	World Bank (WDI)
Population density	Population density is midyear population divided by land area in square kilometers	people per km ²	World Bank (WDI)
Industry value-added	Industry, including construction, value added in percentage of GDP	%	World Bank (WDI)

340 Source: Authors construction

341 **4.3. Descriptive Statistics**

342 Table 2 reports the descriptive statistics for the variables used in empirical analysis. Clean
343 energy finance averages USD78.8 million, with a standard deviation of USD218.4 million,
344 indicating wide dispersion across country-year observations. The distribution is strongly right-
345 skewed, consistent with the concentration of financing in a small number of country-years; the
346 variable is therefore log-transformed in the empirical models.

347 The energy-mix variables point to marked heterogeneity in the composition of electricity
348 generation across the sample. Fossil-fuel generation averages 489.46 kWh per capita, compared
349 with 135.95 kWh per capita for hydropower and only 8.79 and 8.08 kWh per capita for solar
350 and wind, respectively. Several renewable-energy variables take zero minimum values,
351 indicating that some country-years record no generation from these sources. Fossil electricity
352 exceeds each individual renewable source, and hydropower contributes considerably more than
353 solar or wind at the sample level. Carbon intensity of GDP averages 0.390 and ranges from
354 0.045 to 1.675, indicating sizeable cross-country and temporal variation in the carbon efficiency
355 of economic output.

Among the control variables, the ND-GAIN index reveals moderate dispersion around its mean, pointing to relatively homogeneous levels of climate vulnerability and readiness across the sample. GDP per capita averages USD2,640 suggesting the generally low-income profile of the sampled economies. Furthermore, GDP per capita is markedly right-skewed and is log-transformed accordingly. Foreign direct investment averages 4.27% of GDP, with a standard deviation of 6.06 and a range from -17.29% to 64.38%. The negative minimum reflects episodes of net FDI disinvestment or negative net inflows, whereas the very high maximum points to substantial concentration of foreign investment in particular economies and periods. Population density varies widely, consistent with the diverse demographic and spatial structures represented in the sample. Industry value added averages 28.22% of GDP, with the upper bound corresponding to the sample's more industrialized economies. Coal rents remain low on average, though a small number of observations show substantially higher rents.

The descriptive statistics reveal substantial cross-country heterogeneity in energy structure and macroeconomic fundamentals, which motivates the use of panel-data methods controlling for unobserved country and time effects, and supports the logarithmic transformation of the more heavily skewed variables prior to estimation.

Table 2: Descriptive Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
Clean energy finance	840	78830893	2.184e+08	0	2.186e+09
Hydro electricity generation per capita	840	135.953	198.411	0	883.279
Solar electricity generation per capita	840	8.787	46.868	0	637.283
Wind electricity generation per capita	840	8.075	26.632	0	183.508
Fossil electricity generation per capita	840	489.463	981.996	0	4924.738
Carbon intensity	840	0.390	0.259	0.045	1.675
ND-GAIN score	840	40.507	6.209	25.664	57.757
Foreign direct investment (%GDP)	840	4.265	6.059	-17.292	64.384
GDP per capita	840	2640.338	3232.162	142.678	19141.512
Population density	840	93.396	122.993	2.256	634.118
Industry value added (% of GDP)	840	28.218	12.412	8.020	84.349
Coal rents (%GDP)	840	0.808	3.924	0	48.722

Source: Authors computation using STATA 17

5. Results and Discussions

5.1. Diagnostic Tests: Heteroskedasticity, Autocorrelation and Cross-Sectional Dependence

The results of the modified Wald test for groupwise heteroskedasticity and the Wooldridge test for first-order autocorrelation in the panel models for wind, solar, hydroelectricity, and carbon intensity are reported in Table A.1 (see Appendix). The diagnostic results provide consistent evidence of non-spherical disturbances across all four specifications. The Wooldridge test produces complementary evidence of serial dependence. The cross-sectional dependence (CD) test (Table A.2 in the Appendix) indicates substantial evidence of interdependence across the African countries for most of the variables considered.

The combined diagnostic evidence consequently provides a stronger basis for adopting an inference procedure that is robust to heteroskedasticity, serial correlation, and cross-sectional

dependence. Driscoll-Kraay standard errors are designed to provide inference that is robust to these forms of dependence (Hoechle 2007).

5.2. Green finance and renewable-energy development

The analysis investigates the association between international clean energy finance and renewable energy generation across wind, solar, and hydropower using country and year fixed-effects models with Driscoll-Kraay standard errors, complemented by 2SLS-IV estimates for robustness (Table 3). The results of the conventional fixed-effects (FE) reveal a non-significant coefficient of clean energy finance on all the energy technologies considered. This picture changes substantially once the Driscoll-Kraay covariance estimator is applied. Clean energy finance affects now positively and statistically both wind and solar energy generation, whereas the coefficient for hydropower is negative and significant. The estimates suggest that a 1% increase in clean energy finance is associated with increases of approximately 0.0074 kWh per capita in wind and solar generation, respectively, and a decrease of approximately 0.0183 kWh per capita in hydropower generation, holding the other covariates and country/year effects constant. The 2SLS-IV estimates reinforce these patterns, yielding positive coefficients for wind (4.306) and solar (3.567), alongside a negative and highly significant coefficient for hydropower (-5.178).

The contrast across the three renewable technologies is economically meaningful. International clean energy finance is more closely associated with wind and solar deployment than with hydropower generation. This pattern is consistent with differences in technology-specific investment conditions. Wind and solar projects can often be developed incrementally and across geographically dispersed locations, whereas hydropower investments are more dependent on site-specific water resources, geological conditions, large-scale infrastructure, environmental considerations, and lengthy project-development cycles. Consequently, increases in international clean energy finance may not translate proportionately into additional generation across all renewable technologies. This finding is consistent with the broader African literature. Mugume and Bulime (2024) report a positive association between financial development and the renewable energy transition in sub-Saharan Africa, highlighting the role of financial intermediation in channelling capital toward renewable energy investments. Similarly, Belgacem et al. (2023) confirm that green bonds encourage long-term renewable energy investments in emerging economies. The present findings extend this literature by demonstrating that the finance-renewables relationship may vary substantially across technologies, with wind and solar benefiting more consistently than hydropower. However, our finding of a negative and significant coefficient for hydropower contrasts with Nepal et al. (2024), who report hydropower as a primary beneficiary of green finance. This divergence may reflect the different sample composition and period: Nepal et al. (2024) cover 32 developing countries globally over 2003-2020, whereas our study focuses exclusively on 35 African countries through 2023. The negative hydropower coefficient in our study may indicate a portfolio shift in international clean energy finance toward modular wind and solar projects, which have shorter development cycles and lower site-specific risks than large-scale hydropower. The ND-GAIN score has a positive and statistically significant coefficient in the wind and solar energy models under both the Driscoll-Kraay and IV estimations, whereas its

coefficient is negative in the hydropower model. The consistency of these signs across the models suggests that countries with higher climate readiness or preparedness tend to exhibit greater wind and solar generation but lower hydropower generation. This pattern may reflect differences in the investment environments and institutional requirements associated with renewable energy technologies. Countries with stronger institutional and adaptive capacity may be better positioned to identify, prepare, regulate, and implement decentralized renewable energy projects, particularly wind and solar technologies, which can be deployed incrementally and scaled progressively (Bhuiyan et al. 2025). Similarly, the result is consistent with Lee et al. (2024), who indicate that climate risk moderates the effectiveness of green finance in accelerating energy transition, implying that institutional readiness is a precondition for the efficient allocation of green capital. These macro-level findings are consistent with micro-level evidence from Ali (2026), who shows that the effectiveness of financial inclusion in building climate resilience is highly dependent on institutional context and complementary support structures. The negative coefficient for hydropower may therefore reflect differences in technology-specific investment patterns rather than a generalized lack of renewable energy development.

Coal rents are negatively associated with wind generation in all the models, with the coefficient increasing in absolute magnitude from -3.445 under fixed effects to -4.788 under the IV regression. This negative association suggests that economies deriving a greater share of GDP from coal rents may face a stronger structural attachment to conventional energy systems, potentially reducing the relative expansion of wind generation. This finding can be explained by the resource curse literature demonstrating that coal-rent dependence impedes energy transition. Li et al. (2025) find that high coal rents significantly slow down energy transition, creating institutional and economic barriers that lock nations into fossil-fuel pathways.

Industry value added has a negative and significant effect on renewable electricity generation. Under the Driscoll-Kraay estimation, the coefficients are -0.514 for wind, -0.537 for solar, and -2.179 for hydropower. The IV estimates remain negative and significant for wind and solar, whereas the hydropower coefficient is statistically insignificant. This pattern suggests that a higher industrial share of economic activity does not necessarily translate into greater renewable electricity generation. In countries where industrial expansion remains closely dependent on conventional fossil fuels, increasing industrial activity may reinforce existing energy demand without stimulating a corresponding expansion of renewable energy capacity (Ali and Sultanuzzaman 2026). These findings highlight the importance of the energy composition of industrial development, rather than industrial expansion alone, in shaping renewable energy deployment.

The coefficient of GDP per capita is particularly revealing. Under the Driscoll-Kraay specification, GDP per capita is positively associated with all three renewable technologies. The fixed-effects estimates, however, are much less stable: negative for wind and solar but strongly positive for hydro. The reversal in the wind and solar coefficients between the conventional fixed-effects and Driscoll-Kraay specifications is noteworthy, as it indicates that accounting for the dependence structure of the panel materially changes the estimated conditional association between economic development and renewable generation. The positive

469 Driscoll-Kraay estimates are consistent with the possibility that higher-income economies possess greater capacity to finance infrastructure,
470 attract technology, and integrate renewable generation into energy systems (Tudor and Sova 2021).

471 **Table 3: Clean Energy Finance and Renewable Energy**

VARIABLES	Fixed Effect			Driscoll-Kraay standard errors FE			2SLS Instrumental Variables		
	Wind	Solar	Hydro	Wind	Solar	Hydro	Wind	Solar	Hydro
Log of clean energy finance	0.161 (0.295)	0.081 (0.303)	-0.819 (0.736)	0.736*** (0.241)	0.741* (0.383)	-1.832** (0.846)	4.306*** (1.646)	3.567** (1.564)	-5.178*** (1.412)
ND-GAIN score	2.459*** (0.557)	1.541*** (0.572)	-1.177 (1.390)	3.261*** (0.795)	3.025*** (0.986)	-3.219*** (0.975)	3.399*** (0.873)	2.985*** (0.726)	-2.998** (1.391)
Coal rents	-3.445*** (0.379)	-0.410 (0.389)	-1.428 (0.946)	-3.607*** (0.548)	-0.541 (0.343)	-0.964** (0.423)	-4.788*** (0.907)	-0.566 (0.586)	-1.840 (1.196)
Industry value added	-0.196 (0.203)	-0.179 (0.209)	-2.904*** (0.507)	-0.514*** (0.109)	-0.537*** (0.159)	-2.179*** (0.657)	-0.364 (0.230)	-0.519** (0.240)	-1.783* (0.938)
Log of GDP per capita	-8.974** (4.327)	-11.187** (4.443)	41.713*** (10.803)	7.976*** (2.118)	5.347* (2.881)	18.180** (7.171)	-3.062 (4.709)	-2.404 (4.866)	28.974*** (10.489)
Foreign direct investment	0.005 (0.171)	0.086 (0.176)	-0.843** (0.427)	0.138 (0.115)	0.211 (0.245)	-0.952* (0.506)	0.021 (0.201)	0.093 (0.329)	-1.065 (0.739)
Population density	-0.232*** (0.056)	-0.287*** (0.057)	0.411*** (0.140)	-0.107* (0.057)	-0.093 (0.060)	0.167* (0.094)	-0.166*** (0.060)	-0.135** (0.053)	0.210** (0.105)
Constant	-16.280	35.017	-24.572	-166.199***	-143.743***	217.051***			
Observations	628	628	628	628	628	628	526	526	526
R-squared	0.326	0.274	0.129				0.031	-0.031	0.016
Number of id	35	35	35	35	35	35	35	35	35
country effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
year effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
KP rk LM statistic for underidentification							43.46	43.46	43.46
p-value of underidentification LM statistic							3.66e-10	3.66e-10	3.66e-10
KP Wald F statistic for weak identification							25.23	25.23	25.23

472 Source: Authors computation using STATA 17

473 Note: The Kleibergen–Paap rk Wald F statistic of 25.23 exceeds the Stock–Yogo 10% maximal IV size critical value of 19.93, rejecting the null
474 hypothesis of weak instruments. The under-identification test rejects the null hypothesis (KP rk LM = 43.455, $p < 0.001$), confirming that the model
475 is identified. Standard errors in parentheses *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Foreign direct investment is statistically insignificant for wind and solar across specifications. For hydropower, the coefficient is negative under fixed effects (-0.843) and Driscoll-Kraay (-0.952) but loses significance under IV, indicating that the negative FDI-hydro relationship is not robust to endogeneity correction and likely reflects unobserved confounding rather than a stable causal effect. Population density is negatively associated with wind and solar generation under both the fixed-effects and IV specifications, while its relationship with hydropower is positive. This divergence likely reflects land-use and siting constraints: wind and solar require extensive land area and are therefore harder to deploy in densely populated economies, whereas hydropower depends on hydrological and topographic endowments largely independent of population concentration. This pattern aligns with recent spatial econometric evidence from European regions, where population density is inversely related to renewable energy capacity (García-Riazuelo et al. 2025).

5.3.Green Finance, Energy Transition and Carbon Intensity

Table 4 reports the determinants of carbon intensity, measured as annual CO₂ emissions relative to GDP; a negative coefficient therefore reflects an improvement in carbon efficiency. The coefficient on the clean energy finance is negative and significant, 1% increase in clean energy finance is associated with an approximately 0.00002-unit reduction in carbon intensity. The environmental contribution of international clean energy finance thus extends beyond expanding renewable generation capacity to lowering the emissions intensity of economic output itself. This result aligns with Alvi et al. (2025), who find that green finance reduces GHG emissions in OECD countries by supporting renewable energy development, environmental innovation, and energy transition. It also aligns with Ben Abdallah (2025) findings, who shows that green finance reduces CO₂ emissions in both the short and long run. Our findings extend this evidence to the African context, demonstrating that the carbon-reducing effect of green finance operates even in economies with lower institutional readiness and higher fossil-fuel dependence. In the same way, increasing renewable electricity generation, mainly wind and solar, is associated with lower carbon intensity, supporting the transmission mechanism from green finance to renewable-energy development to improved carbon efficiency, consistent with Naeem et al (2023).

The control variables reveal several structural conditions shaping the green finance and carbon intensity relationship. Urbanization is positively associated with carbon intensity across all three specifications: expanding urban activity coincides with higher emissions intensity. Political stability, by contrast, is negatively associated with carbon intensity across the models, consistent with more stable institutional environments supporting better carbon performance. Natural-resource dependence is a further source of carbon pressure: oil rents are positive and highly significant in all specifications, while coal rents are positive and significant in the green-finance and solar specifications. This pattern reflects the persistence of carbon-intensive resource structures in African economies, where economies closely tied to fossil-resource extraction face greater difficulty translating energy-transition investments into rapid reductions in carbon intensity. GDP per capita is negatively and significantly associated with carbon intensity across all models, indicating that higher income corresponds to improved rather than

worsening carbon efficiency, consistent with higher-income economies' greater capacity to adopt efficient technologies and cleaner production processes.

Table 4: Green Finance, Energy Transition and Carbon Emission

VARIABLES	(1) GF-carbon intensity	(2) Wind-carbon intensity	(3) Solar-carbon intensity
Log of clean energy finance	-0.002** (0.001)		
Wind electricity generation per capita		-0.001*** (0.000)	
Solar electricity generation per capita			-0.001*** (0.000)
ND-GAIN score	0.001 (0.002)	0.005** (0.002)	0.004** (0.002)
Urban population	0.007*** (0.001)	0.008*** (0.001)	0.007*** (0.001)
Political stability	-0.002*** (0.000)	-0.001*** (0.000)	-0.001*** (0.000)
Coal rents	0.004*** (0.001)	-0.001 (0.002)	0.004*** (0.001)
Oil rents	0.004*** (0.001)	0.005*** (0.001)	0.005*** (0.001)
Industry value added	0.001 (0.002)	0.001 (0.001)	0.001 (0.001)
Log of GDP per capita	-0.026*** (0.007)	-0.035*** (0.013)	-0.042*** (0.010)
Foreign direct investment	0.001 (0.001)	0.000 (0.001)	-0.000 (0.001)
Population density	-0.000*** (0.000)	-0.001*** (0.000)	-0.001*** (0.000)
Constant	0.385*** (0.074)	0.228 (0.149)	0.311*** (0.110)
Observations	628	840	840
Number of groups	35	35	35

Source: Author's computation using STATA 17

Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

5.4. Energy Mix and Attraction of Clean Energy Finance

This section examines whether renewable-energy development itself makes African countries more attractive destinations for green financial resources (Table 5). Wind and solar electricity generation per capita are positively and significantly associated with clean energy finance, whereas hydropower and fossil-based generation show negative relationships. Renewable-energy development appears to function as a signal of investment readiness: a country already producing wind or solar electricity likely possesses some combination of the infrastructure, regulatory arrangements, technical expertise, grid connections, or institutional experience needed to absorb additional green capital. Existing renewable capacity reduces uncertainty around future projects and eases the organization of subsequent investment. The positive coefficients on wind and solar likely also reflect the growing prominence of these technologies within the international green-finance architecture. This finding aligns with Amoah et al.

(2025), who demonstrate that prior renewable-energy transitions positively influence subsequent climate-finance flows in SSA.

The coefficient on fossil electricity generation per capita is negative and significant: countries with electricity systems more heavily oriented toward fossil generation attract less clean energy finance. This is consistent with a technology-selection mechanism in the international green financial system, where green capital is generally intended for low-carbon investments. High fossil dependence likely signals a less developed renewable project pipeline, weaker renewable infrastructure, or a greater need for transition investment before a country can attract large-scale private or international green capital. The contrast between fossil and renewable sources indicates that the composition of a country's energy system shapes the direction of future financial flows.

The ND-GAIN score is positive and significant across all four specifications, indicating that climate readiness is strongly linked to a country's broader capacity to attract and absorb external energy-related financial resources. Countries with greater adaptive capacity and institutional readiness typically have stronger policy frameworks, administrative capabilities, infrastructure, and investment environments, features that make them more credible recipients of international finance. GDP per capita is likewise positively associated with clean energy finance, reflecting the role of developed financial institutions, regulatory systems, project-development capabilities, and administrative capacity in reducing the transaction costs of international energy investment. FDI is positive and highly significant across all four specifications, with coefficients ranging from 0.046 to 0.053: countries receiving greater FDI inflows also attract more clean energy finance. This likely reflects the broader investment ecosystem that FDI supports, as multinational firms provide technological capabilities, establish supplier networks, strengthen project-development expertise, and raise the visibility of host-country investment opportunities.

Table 5: Energy mix and Green Finance

VARIABLES	Clean Energy Finance			
	(1)	(2)	(3)	(4)
Wind electricity generation per capita	0.012*** (0.004)			
Solar electricity generation per capita		0.012*** (0.004)		
Hydro electricity generation per capita			-0.005** (0.002)	
Fossil electricity generation per capita				-0.001* (0.001)
ND-GAIN score	0.103** (0.044)	0.107** (0.042)	0.130*** (0.039)	0.164*** (0.036)
Log of GDP per capita	2.749*** (0.317)	2.768*** (0.318)	2.879*** (0.336)	2.938*** (0.353)
Foreign direct investment	0.053*** (0.008)	0.051*** (0.009)	0.046*** (0.010)	0.050*** (0.009)
Constant	-8.498***	-8.793***	-9.643***	-11.625***

	(1.587)	(1.584)	(1.679)	(2.038)
Observations	628	628	628	628
Number of groups	35	35	35	35

Source: Author's computation using STATA 17

Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

5.5.Sub-Regional Heterogeneity Analysis

Table 6 shows sub-regional heterogeneity in the relationship between clean energy finance and the African energy mix. Clean energy finance is positively associated with wind and solar generation in Southern Africa, negatively associated with these sources in North Africa, and statistically insignificant in West, East, and Central Africa. In Southern Africa, clean energy finance is positively associated with both wind (1.666) and solar (1.451) generation, while its association with hydropower is negative and significant (-3.823). This pattern indicates that green finance in this sub-region is aligned with the expansion of wind and solar technologies rather than hydro-based generation. The North African results differ: clean energy finance is negatively associated with wind (-1.179) and statistically insignificant for solar and hydropower. The negative wind coefficient contrasts with both the whole-Africa and Southern African results, indicating that the availability of clean energy finance does not guarantee a proportional expansion of any given renewable technology; its allocation and effectiveness depend on regional investment structures, energy-market conditions, institutional arrangements, and existing technological configurations. These regional results complement the aggregate findings; the effect of green finance on the energy transition depends not only on the volume of finance mobilized but also on where it is deployed and under what structural conditions. This heterogeneity helps explain why similar financial instruments produce different energy outcomes across African sub-regions.

Table 6: Green Finance and Energy mix: Sub-Regional Synthesis

Region	Finance Instrument	Wind Coef.	Solar Coef.	Hydropower Coef.	Fossil Coef.
West Africa	Log of clean energy finance	0.462	0.259	-0.344	0.440
	ND-GAIN score	0.777	1.058*	1.317	5.849***
	Coal rents	-3.752***	-0.519	0.142	-1.827
	Industry value added	-1.178**	-0.768	-0.234	-0.568
	Log of GDP per capita	8.587**	3.446	12.934	65.463***
	Foreign direct investment	0.849*	0.527*	-0.423	-1.524
	Population density	-0.104	0.037	-0.144	0.894*
East Africa	Log of clean energy finance	-0.309	-0.084	0.030	0.440
	ND-GAIN score	0.906	0.203	-7.098**	5.849***
	Coal rents	0.000	0.000	0.000	-1.827
	Industry value added	-4.650**	-0.160	-1.987	-0.568
	Log of GDP per capita	19.709***	1.943	-11.920	65.463***
	Foreign direct investment	-3.075*	-0.034	-0.776	-1.524
	Population density	-0.009	0.006	0.691***	0.894*
Central Africa	Log of clean energy finance	0.004	0.080	-0.890	0.440
	ND-GAIN score	0.004	1.104	-4.968	5.849***

	Coal rents	0.000	0.000	0.000	-1.827
	Industry value added	-0.003	0.116*	-3.609**	-0.568
	Log of GDP per capita	0.015	1.327	34.432	65.463***
	Foreign direct investment	0.000	0.035	-0.301	-1.524
	Population density	-0.001	0.143***	0.847	0.894*
Southern Africa	Log of clean energy finance	1.666**	1.451*	-3.823**	0.440
	ND-GAIN score	0.335	12.137***	-23.914***	5.849***
	Coal rents	-5.042**	-3.622	-23.780***	-1.827
	Industry value added	-0.642	-0.444	-3.202**	-0.568
	Log of GDP per capita	0.635	1.683	34.057	65.463***
	Foreign direct investment	0.239	0.779	-0.969	-1.524
	Population density	0.092	0.021	-0.003	0.894*
North Africa	Log of clean energy finance	-1.179**	-0.764	0.334	0.440
	ND-GAIN score	15.865***	4.162**	1.847	5.849***
	Coal rents	1.318	-4.695	5.768	-1.827
	Industry value added	0.038	-0.386	-2.039**	-0.568
	Log of GDP per capita	-21.107	-7.808	39.637**	65.463***
	Foreign direct investment	0.788*	0.066	0.388	-1.524
	Population density	1.440**	1.080*	-2.729***	0.894*

582 Source: Author's computation using STATA 17

583 *** p<0.01, ** p<0.05, * p<0.1

584 6. Conclusion

585 This study examines the interconnected relationship between green finance, energy transition,
586 and carbon emissions in Africa. The econometrics regressions yield four main findings. First,
587 international clean energy finance is positively and robustly associated with wind and solar
588 electricity generation, but negatively associated with hydropower. This result supports an
589 energy-stacking interpretation of Africa's transition, in which new financial resources are
590 layered unevenly across the existing energy portfolio rather than expanding all renewable
591 sources simultaneously. Second, clean energy finance is associated with lower aggregate carbon
592 intensity, operating in part through the renewable-generation channel. Wind and solar
593 generation are themselves associated with lower carbon intensity, tracing a transmission
594 pathway from finance to renewable deployment to improved carbon efficiency. The persistence
595 of oil- and coal-rent dependence as significant positive correlates of carbon intensity, however,
596 indicates that this pathway remains constrained by the structural weight of fossil-resource-
597 dependent economic activity in Africa. Third, the reverse-causality analysis indicates that the
598 finance-transition relationship is not unidirectional. Countries with more developed wind and
599 solar generation attract significantly more clean energy finance, while greater reliance on fossil
600 generation is associated with significantly less. Fourth, the sub-regional analysis shows that the
601 finance-renewable-energy relationship varies across the continent. The positive association
602 between clean energy finance and wind and solar generation identified at the continental level
603 is driven predominantly by Southern Africa, while the relationship is negative in North Africa.
604 This regional variation cautions against treating green finance for Africa as a single, continent-
605 wide policy lever. The same volume and type of financial flow can produce different energy
606 outcomes depending on regional institutional capacity, market structure, and the composition
607 of existing energy infrastructure.

These findings carry several implications for the design of climate-finance instruments intended to accelerate Africa's low-carbon transition. Given the divergent responsiveness of wind, solar, and hydropower to clean energy finance, international financiers and domestic policymakers should consider technology-differentiated financing instruments and risk-mitigation mechanisms, for instance, longer-tenor, patient capital instruments tailored to hydropower's extended development cycles, alongside more modular, rapidly deployable financing facilities for wind and solar. The consistent role of the ND-GAIN score across nearly all specifications indicates that investments in institutional and adaptive readiness are not a co-benefit of climate policy but a structural precondition for the effective absorption of green finance; complementary technical-assistance and capacity-building programmes should therefore accompany capital mobilization efforts, particularly in lower-readiness countries. The evidence of a signaling-driven, self-reinforcing dynamic in finance attraction supports blended or concessional finance mechanisms targeted at countries with limited existing renewable capacity, to help them overcome the initial credibility barrier rather than allowing green-finance flows to concentrate further among already-advanced adopters.

The study has several limitations. Country-level data may obscure within-country heterogeneity in energy systems and green-finance allocation. The analysis focuses on the volume rather than the effectiveness of green finance, and the study period may not fully capture long-term transition dynamics. Future research could address these limitations using micro-level data, examining the quality of green-finance instruments, and exploring nonlinear or dynamic transition pathways across African economies.

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