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Climate Vulnerability, Green Transition and Sustainable Development in Africa: Evidence from KRLS and PCSE Models

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ABSTRACT

Climate change constrains sustainable development in Africa, but the effects of transition policies depend on whether they improve energy access, productivity, and resilience. This study examines how energy productivity and renewable energy consumption moderate the climate stress-development relationship in 43 African countries from 2000 to 2024. Sustainable development is measured using the SDG Index and Human Development Index, while climate stress is captured by climate vulnerability and carbon emissions. Kernel Regularized Least Squares and panel-corrected standard errors are applied. Results show that climate vulnerability consistently weakens development outcomes. Energy productivity improves development and reduces the adverse effect of vulnerability, whereas renewable energy shares produce mixed outcomes because they often reflect traditional biomass rather than modern energy. Effects vary across income groups, with stronger vulnerability penalties in poorer countries. Policies should prioritise reliable modern energy, productive energy use, clean cooking, and targeted resilience investment rather than aggregate renewable energy shares alone.

Keywords: Climate Vulnerability, Energy Productivity, Green Transition, Sustainable Development, Africa
JEL Classifications: Q54, Q56, O55, C23

1. INTRODUCTION

Climate extremes are becoming more frequent while many countries still confront poverty reduction, structural transformation, fiscal consolidation, and human development challenges. Climate stress affects development through agricultural productivity, infrastructure damage, disease burdens, public expenditure pressure, and investment uncertainty (Assoua et al., 2024; Trisos et al., 2022). These effects are larger where households depend on climate-sensitive livelihoods and governments have limited fiscal space for adaptation, reconstruction, and social protection (Okunade et al., 2025a; Kabemba, 2022).

Africa contributes only a small share of global energy use and energy-related emissions, yet it carries a large energy access deficit. The International Energy Agency reports that Africa accounts for about 6% of global energy use and less than 3% of global energy-related carbon dioxide emissions, while more than 600 million people lack electricity access and nearly one billion lack clean cooking access (International Energy Agency [IEA], 2022; International Renewable Energy Agency, 2022). Africa's green transition must therefore expand modern energy access, improve reliability, reduce biomass-related health and time burdens, and mobilize finance for grids, clean cooking, storage, and adaptation. When it raises energy productivity, lowers effective energy costs, expands reliable electricity, and supports clean cooking, green transition can strengthen firm competitiveness, protect household welfare, and reduce exposure to fuel-price shocks (Dhayal et al., 2025; Marinov, 2025). It can also disappoint if financed through regressive price increases, if renewable capacity does not improve reliability, or if headline renewable shares mainly reflect traditional biomass. The relevant question is therefore whether specific transition channels moderate the development costs of climate vulnerability.

Recent studies already link climate vulnerability, green innovation, energy security, and sustainable development.

Xiao and Fei (2024), Tran et al. (2025), Baita et al. (2025), Isik et al. (2025), and Filipovic et al. (2022) show that this nexus has been examined from several angles. This study therefore makes a narrower claim: It examines how climate vulnerability, energy productivity, and renewable energy shares jointly relate to welfare-oriented development outcomes in an African panel, and whether these relationships differ by income group. First, the study links climate vulnerability and transition indicators to the SDG Index Score and the Human Development Index rather than relying only on emissions or aggregate output. Second, it separates energy productivity from renewable energy share because the two indicators capture different transition mechanisms. Third, it reports income-group estimates to show whether the vulnerability-development association differs across countries with different fiscal capacity, electrification levels, and energy system structures.

2. LITERATURE REVIEW

2.1. Conceptual Foundations

Sustainable development in Africa is shaped by climate exposure and the capacity of economies to generate inclusive growth, employment, public services, and human capital. Climate change is therefore a development constraint that can slow structural transformation and reinforce inequality where adaptation is underfunded (Raihan et al., 2026; Trisos et al., 2022; Steiner, 2019). A green transition can be understood as a shift in energy and production systems toward lower-carbon and more resource-efficient pathways, but in Africa its development relevance depends on affordability, reliability, productive use, and distributional effects (Abdallah, 2025).

First, renewable energy shares do not necessarily indicate modern energy transition because high shares may reflect traditional biomass rather than solar, wind, geothermal, hydro, or other productive energy sources (Guesmi et al., 2024). Second, energy productivity captures how efficiently economies convert energy inputs into output and welfare (Bai and Xing, 2025; Okunade et al., 2025b). These distinctions justify treating energy productivity and renewable share as separate moderators whose development value depends on energy access, grid reliability, and complementary investment. Energy pricing reforms, subsidy changes, and investment decisions shape who bears costs and who gains access (Agrawal et al., 2024; Bai and Xing, 2025). Where credit markets are shallow, public investment management is weak, and energy access is low, welfare gains are more likely to come from reliability and affordability improvements than from technology adoption alone (Marinov, 2025; Okunade et al., 2025b). These considerations motivate a design that tests transition indicators as moderators and examines income-group heterogeneity.

2.2. Empirical Evidence

Xiao and Fei (2024), Tran et al. (2025), Baita et al. (2025), and Isik et al. (2025) show that climate vulnerability can shape green innovation, green growth, and energy vulnerability. Their findings confirm that the climate-transition-development relationship is not new, but they leave room for Africa-wide evidence using welfare-oriented outcomes and a distinction between energy productivity and renewable energy shares. African evidence also links energy transition variables to growth, emissions, and environmental indicators, often finding that renewables support long-run performance when institutions and infrastructure are supportive (Guan et al., 2025; Panja et al., 2025). Other studies show that vulnerability to climate shocks can reduce growth and welfare and that adaptation capacity and governance condition outcomes (Aurelien, 2025; Trisos et al., 2022).

Climate vulnerability is expected to depress development outcomes, while energy productivity and renewable energy shares may weaken or strengthen this association depending on whether they improve productive energy use and modern access. The remaining gap is specific: SDG Index and HDI outcomes are less common in Africa-wide transition studies; energy productivity is often not separated from renewable share; and income-group heterogeneity deserves explicit treatment because African countries differ sharply in grid reliability, fiscal space, investment capacity, and clean-cooking access.

2.3. Trends of Climate Change, Green Transition, and Sustainable Development in Africa

ND-GAIN vulnerability scores remain high in many low-income and conflict-affected settings, while upper-middle-income economies generally show lower vulnerability and stronger readiness (Figure 1). Carbon dioxide emissions excluding land-use change and forestry in Figure 2 have increased as energy demand and industrial activity expanded, but Africa's per capita emissions remain low relative to global averages (Guesmi et al., 2024). This supports a transition strategy that expands modern energy access while avoiding high-emission lock-in.

Energy productivity (Figure 3) has improved in some countries but remains constrained by transmission losses, weak industrial efficiency, and limited regulatory capacity (Kabemba, 2022; Blimpo et al., 2024). Renewable energy shares are high in several low-income countries, often because biomass remains central to final energy consumption (Figure 4). SDG Index and HDI outcomes generally improve over time (Figures 5 and 6), but progress remains sensitive to climate shocks, inflation, commodity cycles, and fiscal stress (Sachs et al., 2024; Tiwari et al., 2024).

Figure 1: Trend of climate vulnerability index (CVI) from 2000 to 2024

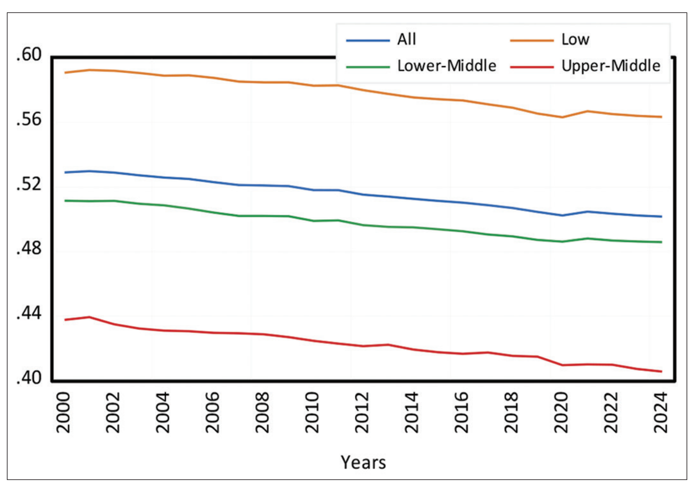


Figure 2: Trend of total carbon dioxide (CO_2) emissions (% change from 1990) from 2000 to 2024

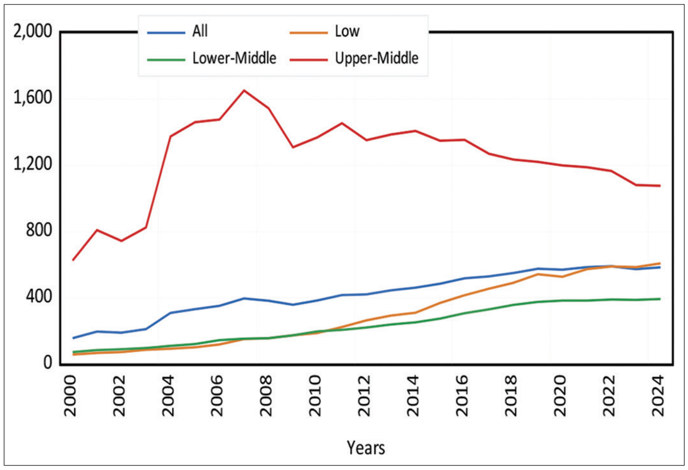


Figure 3: Trend of green transition (Energy productivity) from 2000 to 2024

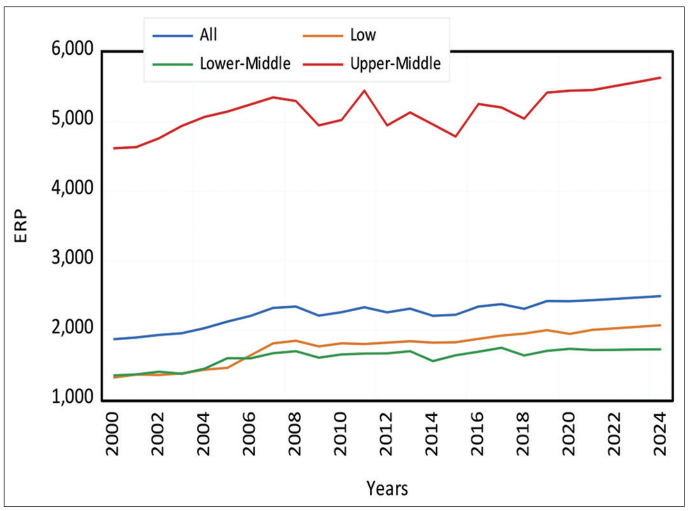


Figure 4: Trend of renewable energy consumption (% of total fine energy consumption) from 2000 to 2024

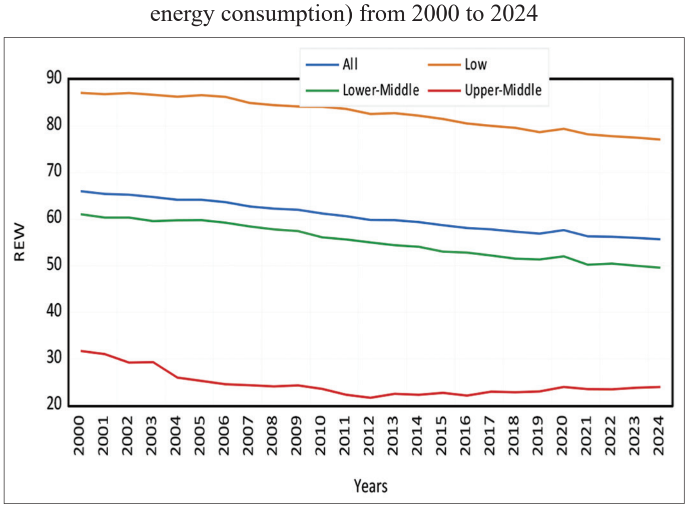


Figure 5: Trend of sustainable development index (SDGI) from 2000 to 2024

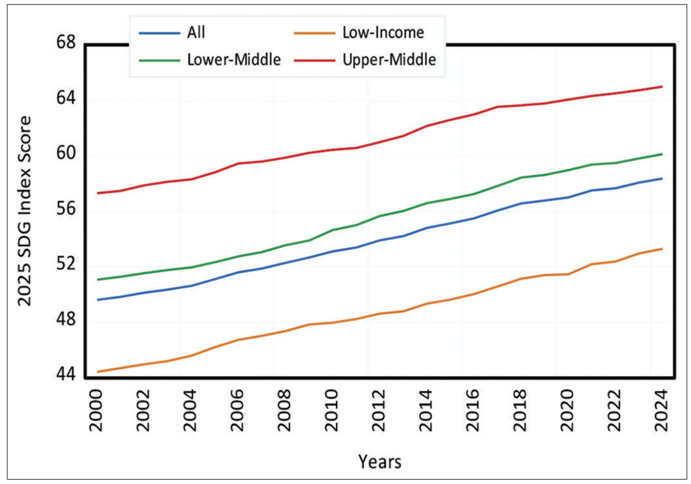
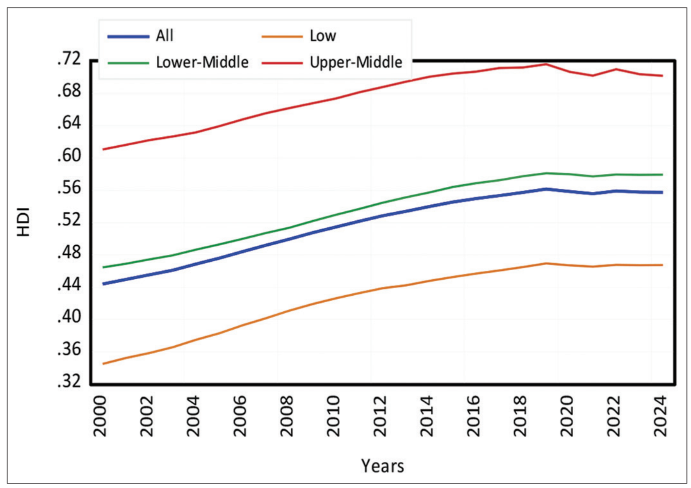


Figure 6: Trend of human development index (HDI) from 2000 to 2024



Vulnerability and development are generally negatively related, while transition indicators appear more development-enhancing when they reflect modern energy access and efficiency (Quan et al., 2025). The relationship is unlikely to be linear because early increases in renewable share may capture biomass dependence, whereas later modern renewables and efficiency gains may matter more once grids, skills, and investment frameworks mature (Dhayal et al., 2025; Yu et al., 2026). Income-group comparisons reinforce this point: Upper-middle-income countries show higher SDG and HDI levels and clearer energy productivity gains, while low-income countries face the highest vulnerability and the strongest infrastructure constraints.

3. METHODOLOGY AND DATA ISSUES

3.1. Study Area, Data Sources, Variables, and Measurement

The analysis covers 43 African countries with sufficient data for 2000 to 2024. Countries are grouped using the World Bank income classification based on Atlas-method gross national income per capita (World Bank, 2025). The list of 43 Selected African Countries based on 2025 World Bank income classification is provided in Appendix A. The dependent variables are the backdated SDG Index Score from

Table 1: Variable definitions and sources

S. No.	Variable	Definition/Description/ Measurements	Source
1.	SDGI	SDG index score, is a welfare-oriented sustainable development	SDR, 2025
2.	HDI	Human development index (index from 0 to 1), indicating capability-based development outcome	UNDP, 2024
3.	CAB	Total carbon dioxide (CO_2) emissions (% change from 1990)	WDI, 2026
4.	CVI	Climate vulnerability index. Higher values indicate greater vulnerability	ND-GAIN, 2026
5.	ERP	Environmental and resources productivity (Energy productivity)	OECD, 2025
6.	REW	Renewable energy consumption as a percentage of total final energy consumption. It is an energy-use pressure indicator	WDI, 2026
7.	POP	Annual population growth (%)	WDI, 2026
8.	ACE	Access to electricity as a percentage of total population	WDI, 2026
9.	PSE	Gross primary school enrolment ratio, Education-access proxy	WDI, 2026

Data were sourced from Sustainable Development Report (SDR), 2025 of Sachs et al. (2024); United Nations Development Programme (UNDP) Sustainable Report, 2024; Notre Dame Global Adaptation Initiative (ND-GAIN); World Development Indicators (WDI); Organisation for Economic Co-operation and Development (OECD) Environment Statistics on "Green Transition"

Sachs et al. (2024) and the Human Development Index. Climate stress is measured using the Notre Dame Global Adaptation Initiative (ND-GAIN) vulnerability index and carbon dioxide emissions excluding land-use change and forestry. Green transition is measured using energy productivity and renewable energy consumption as a percentage of total final energy consumption. The renewable variable is interpreted cautiously because it combines modern renewables with traditional biomass in some settings. Controls include population growth, access to electricity, and gross primary school enrolment as a basic education participation proxy rather than a literacy rate, since gross enrolment can exceed 100%. Energy productivity and selected scale variables are log-transformed to reduce skewness and support semi-elasticity interpretation (Burbidge et al., 1988; Bellemare and Wichman, 2020). The description, measurements and sources of variables are provided in Table 1.

3.2. Econometric Strategy and Model Specification

The baseline objective is to estimate conditional associations between climate stress, green transition indicators, and sustainable development, and to test whether transition indicators moderate climate-stress effects. The interaction terms therefore have a moderation interpretation; they do not test mediation because no sequential mediator model is estimated.

$$SD_{it} = f(CMC_{it}, GTR_{it}, X_{it}) \quad (1)$$

where SD_{it} denotes sustainable development indicators, CMC_{it} denotes climate change indicators and GTR_{it} denotes green transition indicators. The function f (.) is allowed to be nonlinear.

$$SD_{it}=\alpha_i+\tau_t+\beta_1 CVI_{it}+\beta_2 CAB_{it}+\beta_3 ERP_{it}+\beta_4 REW_{it}+\delta_1(CVI_{it}*ERP_{it})+\delta_2(CVI_{it}*REW_{it})+\delta_3(CAB_{it}*ERP_{it})+\delta_4(CAB_{it}*REW_{it})+\gamma X_{it}+\varepsilon_{it} \quad (2)$$

Where SD_{it} is proxied by the SDG Index Score or the Human Development Index in country i at time t, CMC_{it} is proxied by climate vulnerability (CVI_{it}), and total carbon emissions excluding land use change and forestry (CAB_{it}). Also, green transition (GTR_{it}) is proxied by energy productivity (ERP_{it}), and the renewable energy share (REW_{it}), and X_{it} contains controls for population growth, access to electricity, and Education-access indicator. α_i captures country-specific effects, and τ_t captures common time dynamics where included.

Kernel regularized least squares (KRLS) is used as a flexible nonparametric estimator because it reduces functional-form restrictions and returns interpretable average marginal effects (Hainmueller and Hazlett, 2014). The implementation should use a Gaussian radial basis function kernel, standardized predictors, and regularization selected by leave-one-out cross-validation (Ferwerda et al., 2014). For robustness, the study estimates conventional panel models with panel-corrected standard errors (PCSE). PCSE is useful as a sensitivity check for heteroskedasticity and contemporaneous correlation in time-series cross-section data (Beck and Katz, 1995). The panel has N = 43 and T = 25, so it should not be described as a case where T is larger than N. The robustness models use the same covariates and interaction terms, with country fixed effects and common time dynamics captured where appropriate.

4. DATA ANALYSIS AND INTERPRETATIONS

4.1. Preliminary Analyses and Diagnostic Evidence

Table 2 reports the full-sample descriptive statistics and correlations. Average SDG Index performance is 53.9, while the HDI averages 0.52. The mean climate vulnerability score of 0.52 indicates substantial exposure and sensitivity to climate risks. Renewable energy share averages 60.5%, consistent with the continued importance of biomass and hydro in final energy use. Access to electricity averages 45.4%, with wide dispersion across countries. Correlations show that electricity access is strongly positive for SDG and HDI outcomes, while renewable energy share is negatively correlated with both indicators, consistent with the interpretation that high renewable shares in many low-income settings reflect biomass dependence rather than modern energy transition. Table 3 reports diagnostic tests. Im et al. (2003)'s IPS, CIPS, and PESCADF tests indicate that most variables are integrated of order one, while others become stationary after differencing. Pesaran CD and related tests reject cross-sectional independence, consistent with shared shocks such as commodity cycles, global financial conditions, and regional climate patterns (Pesaran, 2004, 2007). Westerlund (2007) tests support cointegration among climate stress, transition indicators, and development outcomes, while the Wooldridge test indicates serial correlation.

4.2. Main and Robustness results

4.2.1. All African countries

Tables 4 and 5 report full-sample KRLS and PCSE results for the SDG Index and HDI. Across specifications, higher climate vulnerability is associated with lower development outcomes. In the KRLS specification that includes the vulnerability-renewable interaction, a one-unit increase in vulnerability is associated with a reduction of about 0.37 points in the SDG Index and 0.057 in HDI,

Table 2: Descriptive characteristics and correlation analyses of the variables

VAR.	SDGI [1]	HDI [2]	CVI [3]	CAB [4]	ERP [5]	REW [6]	POP [7]	ACE [8]	PSE [9]
Obs.	1075	1075	1075	1075	1075	1075	1075	1075	1075
Mean	53.93	0.52	0.52	423.5	2251.5	60.49	2.41	45.35	97.63
Std. Dev.	7.63	0.11	0.07	1099.2	4112.3	29.57	0.95	29.71	21.55
Min.	39.0	0.26	0.35	−54.39	53.9	0.09	−0.92	1.3	25.57
Max.	72.77	0.81	0.66	9937.1	15582.8	98.3	6.41	100.6	156.6
1	1.00								
2	0.84	1.00							
3	0.04	0.06	1.00						
4	−0.78	−0.83	0.01	1.00					
5	−0.04	0.05	0.19	−0.04	1.00				
6	−0.62	−0.70	−0.19	0.71	−0.17	1.00			
7	−0.51	−0.45	0.05	0.46	0.07	0.38	1.00		
8	0.75	0.80	0.12	−0.73	−0.04	−0.57	−0.34	1.00	
9	0.38	0.36	−0.10	−0.21	0.05	−0.03	−0.24	−0.01	1.00

SDGI, HDI, CVI, CAB, ERP, REW, POP, ACE, and PSE represent sustainable development index, human development index, climate vulnerability index, carbon dioxide (CO_2) emissions, Environmental and resources productivity (Energy productivity), Renewable energy consumption, Population growth, Access to electricity, and Primary school enrollment ratio respectively

Table 3: Cross-sectional dependence, panel unit root, autocorrelation & cointegration tests

Variables	SDGI [1]	HDI [2]	CVI [3]	CAB [4]	ERP [5]	REW [6]	POP [7]	ACE [8]	PSE [9]
IPS (Level)	−0.621	−0.753	−1.329	−2.204**	−1.52	−1.112	−0.954	-1.452	-2.207***
IPS (First diff)	−4.78***	−2.88***	−6.02***		−4.88***	−4.94***	−3.085***	-7.17***	
CIPS (Level)	−1.864	−1.890	−1.004	−2.68***	−1.834	−1.691	−1.413	-3.247***	-1.886
CIPS (First diff)	−4.397***	−4.084***	−2.434***		−4.5***	−4.49***	−2.948***		-4.344***
PESCADF (level)	−0.802	1.054	−1.210	−4.67***	−0.447	0.656	−4.506***	-5.003***	-8.88***
PESCADF (First D)	−7.877***	−5.626***	−10.63***		−12.9***	−9.57***			
Status	I (1)	I (1)	I (1)	I (0)	I (1)	I (1)	I (1)	I (1)	I (0)
CD-test	132.8***	74.5***	65.6***	97.3***	88.1**	66.4***	18.5***	134.1***	52.7***
Pesaran's test of cross-sectional independence	8.709***, Pr=0.0000								
Friedman's test of cross-sectional independence	78.144***, Pr=0.0006								
Frees' test of cross-sectional independence	7.933*** alpha=0.1035 (10%); 0.1350 (5%); 0.1947 (1%)								
Autocorrelation (Wooldridge) test	F (1, 42)=217.313***, Prob.=0.0000								
Westerlund statistic (cointegration)	Variance ratio=9.29***, Prob.=0.000								

***P<0.01, **P<0.05, *P<0.1 (10%)

holding other covariates constant. This is consistent with evidence that climate risk depresses welfare through productivity losses, health burdens, infrastructure damage, and fiscal pressure (Trisos et al., 2022; Aurelien et al., 2025). In the SDG models, the emissions term is positive and significant, which may reflect the stage of many African economies where higher energy use still accompanies basic services and industrialisation (Tiwari et al., 2024). In HDI models, the coefficient is generally negative and often significant, suggesting that fossil-based emissions can coincide with weaker capability outcomes after controls are included.

Energy productivity is the clearest transition channel in the pooled estimates. Its main effect varies when interactions are introduced, but positive interaction terms between energy productivity and climate stress suggest that more efficient energy use can reduce the vulnerability-development penalty (Tables 4 and 5). It means that economies that convert energy more efficiently into output and services appear less exposed to some development losses associated with climate stress (Oyadeyi and Oyadeyi, 2025; Okunade et al., 2025b).

In many African economies, renewable energy consumption includes fuelwood, charcoal, and other traditional biomass (Agrawal et al., 2024). High renewable shares can therefore coexist with low electricity access, weak productive energy use, and clean-cooking deficits. The interaction terms suggest that renewable energy is development-enhancing only when it reflects modern, reliable, and productive energy use. Access to electricity remains strongly positive in all models, while population growth is generally negative, indicating pressure on per capita service provision when investment does not keep pace.

Access to electricity is strongly positive and significant in all models for both dependent variables, confirming that electrification remains a core constraint on development in Africa. The PCSE robustness results in Table 5 broadly confirm the role of green transition as a moderating channel, particularly through the interaction terms, even though some main effects differ in sign. Overall, the combined evidence suggests that climate vulnerability is a persistent drag on African development, but that green transition progress, especially higher energy productivity and a shift toward modern renewables, can reduce the sensitivity of development outcomes to climate stress.

4.2.2. Upper middle-income countries

Tables 6 and 7 report upper-middle-income results. KRLS estimates show that climate vulnerability remains negatively associated with both development measures, although the small

Table 4: Results of machine learning tool - kernel-based regularized least squares (KRLS) – non-parametric test

Variables	Sustainable development (SDG Index)						Sustainable development (Human Development Index [HDI])					
	(1)	(2)	(3)	(4)	(5)	(6)	(1)	(2)	(3)	(4)	(5)	(6)
cvi	−1.03***	−0.524***	−0.519***	−0.449***	−0.518***	−0.367***	−0.713***	−0.205***	−0.201***	−0.237***	−0.203***	−0.057**
	(−24.99)	(−19.67)	(−19.540)	(−18.203)	(−19.464)	(−14.735)	(−21.537)	(−10.026)	(−9.740)	(−12.374)	(−9.976)	(−2.954)
lcab	0.02***	0.013***	0.092***	0.013***	0.012***	0.013***	−0.0145	−0.006***	−0.006***	−0.056***	−0.124**	−0.0059***
	(10.699)	(15.196)	(13.068)	(15.348)	(19.016)	(14.672)	(−1.019)	(−9.097)	(−11.815)	(−8.518)	(−2.612)	(−9.065)
lerp	0.06***	−0.0043*	−0.0153*	0.011***	−0.0053**	−0.054***	0.061***	0.022***	0.020***	−0.203***	0.022***	0.019***
	(3.078)	(−1.661)	(−6.268)	(5.704)	(−2.166)	(−2.169)	(10.986)	(11.029)	(10.681)	(13.583)	(11.379)	(10.090)
lrew	−0.29***	−0.040***	−0.039***	−0.041***	−0.041***	0.025***	−0.059***	−0.047***	−0.045***	−0.046***	−0.037***	−0.032***
	(8.336)	(−15.398)	(−15.32)	(−16.434)	(−17.521)	(12.405)	(−13.194)	(−23.376)	(−22.739)	(−23.717)	(−20.686)	(−20.914)
lcab_lerp			0.023***						0.0345**			
			(13.988)						(2.676)			
cvi_lerp				0.021***						0.013***		
				(7.346)						(5.563)		
lcab_lrew					0.069***						0.012***	
					(6.558)						(15.165)	
cvi_lrew						0.375***						−0.034***
						(19.582)						(−23.264)
pop		−0.065**	−0.067***	−0.007***	−0.066***	−0.067***		−0.0314	−0.0425	−0.00657	−0.049	−0.016***
		(−3.249)	(−3.405)	(−3.589)	(−3.341)	(−3.296)		(−0.203)	(−0.278)	(−0.432)	(−0.032)	(−0.104)
lace		0.106***	0.102***	0.101***	0.105***	0.103***		0.094***	0.095***	0.092***	0.094***	0.093***
		(21.611)	(21.439)	(21.165)	(21.887)	(21.249)		(24.861)	(25.540)	(24.952)	(25.674)	(24.941)
lpse		0.220***	0.210***	0.226***	0.221***	0.218***		0.183***	0.185***	0.185***	0.189***	0.191***
		(15.971)	(15.490)	(17.016)	(16.346)	(16.002)		(17.225)	(17.542)	(17.909)	(18.280)	(18.231)
Obs.	1,075	1,075	1,075	1,075	1,075	1,075	1,075	1,075	1,075	1,075	1,075	1,075
Lambda	0.7073	0.4897	0.4895	0.5396	0.5394	0.5394	0.7427	0.4897	0.4895	0.5396	0.5394	0.5394
Eff. df.	34.64	96.77	96.24	91.75	92.57	90.66	34.2	96.77	96.24	91.75	92.57	90.66
R-squared	0.841	0.9573	0.9565	0.956	0.9545	0.9545	0.8412	0.9616	0.9602	0.9596	0.9595	0.9592
Looloss	25.4	7.698	8.033	7.834	8.241	8.072	20.25	5.479	5.68	5.705	5.75	5.748
No. of id	43	43	43	43	43	43	43	43	43	43	43	43

t-statistics in parentheses. ***P<0.01, **P<0.05, *P<0.1

Table 5: Results of correlated panels corrected standard errors (PCSEs) – parametric test (robustness analysis)

Variables	Sustainable development (SDG Index)						Sustainable development (Human Development Index [HDI])					
	(1)	(2)	(3)	(4)	(5)	(6)	(1)	(2)	(3)	(4)	(5)	(6)
cvi	−1.292**	−0.449***	−0.449***	−0.269***	−0.505***	−0.264	−1.051***	−0.441***	−0.443***	−0.609***	−0.357***	0.597***
	(−31.65)	(−12.09)	(−11.94)	(−4.599)	(−11.73)	(−1.601)	(−45.84)	(−14.85)	(−14.95)	(−16.01)	(−10.46)	(6.139)
lcab	−0.0194*	−0.0582	−0.0851	−0.0158	−0.228***	−0.00573	−0.0109	−0.0138**	−0.059***	−0.0147**	0.0329**	−0.0230**
	(−1.658)	(−0.106)	(−0.281)	(−0.282)	(−4.093)	(−1.085)	(−1.201)	(−3.087)	(−4.037)	(−3.270)	(8.195)	(−4.556)
lerp	0.195**	−0.013***	0.0152*	0.0239**	−0.130***	−0.125***	0.00247	0.00138	−0.0962**	−0.0333**	0.0141*	0.0216**
	(3.078)	(−4.872)	(1.733)	(2.191)	(−5.162)	(−4.760)	(1.552)	(1.643)	(−2.893)	(−5.796)	(1.771)	(2.252)
lrew	0.22***	−0.024***	0.236***	−0.218***	−0.488***	0.0351**	−0.251***	−0.286***	−0.287***	−0.302***	0.0932*	0.0567**
	(8.336)	(−19.67)	(20.21)	(−18.00)	(−8.153)	(2.553)	(−16.98)	(−35.82)	(−36.19)	(−33.98)	(1.959)	(7.085)
lcab_lerp			0.0404						0.002***			
			(0.274)						(3.487)			
cvi_lerp				0.716***						0.067***		
				(2.828)						(6.113)		
lcab_lrew					0.0454**						0.068***	
					(3.999)						(8.407)	
cvi_lrew						0.148***						0.215***
						(4.194)						(10.58)
pop		−0.233***	−0.233***	−0.237***	−0.0203**	−0.236***		−0.0383**	−0.0386**	−0.00343*	−0.084***	−0.0420**
		(−10.36)	(−10.40)	(−10.85)	(−7.644)	(−10.80)		(−2.070)	(−2.171)	(−1.801)	(−7.554)	(−2.330)
lace		0.134***	0.134***	0.133***	0.136***	0.123***		0.129***	0.127***	0.131***	0.127***	0.113***
		(20.48)	(19.38)	(20.10)	(21.26)	(24.29)		(30.22)	(29.09)	(28.28)	(31.37)	(26.48)
lpse		0.335***	0.335***	0.334***	0.310***	0.336***		0.245***	0.246***	0.246***	0.282***	0.247***
		(17.82)	(17.78)	(18.24)	(18.98)	(17.69)		(15.91)	(16.38)	(15.38)	(15.20)	(16.23)
Constant	5.476**	3.971***	3.976***	3.864***	4.222***	3.669***	1.173***	0.182***	0.205***	0.282***	−0.194***	−0.259***
	(695.8)	(82.84)	(77.03)	(74.51)	(51.19)	(53.19)	(266.5)	(5.184)	(5.868)	(7.659)	(−2.756)	(−5.061)
Obs.	1,075	1,075	1,075	1,075	1,075	1,075	1,075	1,075	1,075	1,075	1,075	1,075
R-squared	0.621	0.772	0.772	0.773	0.774	0.774	0.713	0.845	0.846	0.846	0.852	0.851
No. of id	43	43	43	43	43	43	43	43	43	43	43	43
Chi-square	8994	23262	27431	28807	21270	21269	28547	32259	36544	41860	75173	28451

z-statistics in parentheses. ***P<0.01, **P<0.05, *P<0.1

subgroup of seven countries requires caution. In the interaction specification, higher vulnerability is associated with declines of about 0.40 points in the SDG Index and 0.14 in HDI. Emissions growth is less stable in this group: it is not significant for the SDG Index in the preferred KRLS specification but is positive and significant for HDI, consistent with economies where industrial activity and energy use remain linked to income and capabilities.

Green transition indicators appear to play a stronger moderating role in this group. Energy productivity is positive in the SDG model, while the vulnerability-renewable interaction is positive for both SDG and HDI outcomes. This suggests that renewable penetration, supported by grids, efficiency, and infrastructure, may weaken the development penalty from vulnerability (Quan et al., 2025).

4.2.3. Lower middle-income countries

Tables 8 and 9 focus on lower-middle-income countries. In the interaction specification, vulnerability reduces the SDG Index by about 0.26 points and HDI by about 0.41. These countries face urban exposure, water stress, agricultural sensitivity, and fiscal volatility that can transmit climate shocks into public services and household welfare (Assoua et al., 2024; Oyadeyi and Oyadeyi, 2025). Emissions growth is negative and significant for the SDG Index in the preferred specification, suggesting that emissions expansion may reflect congestion, pollution, and inefficient energy systems more than inclusive development. Energy productivity is positive and significant for both outcomes, reinforcing its relevance for countries that are industrialising and urbanising. Renewable shares remain negative, likely reflecting traditional biomass and incomplete translation of modern renewable deployment into broad human development gains (Panja et al., 2025; Abdallah, 2025).

The moderation results suggest that renewable energy can reduce the marginal development cost of vulnerability when it reflects modern renewables and improved access. Decentralised solar, grid-scale renewables, and clean-cooking investments can stabilise energy services during climate shocks and reduce energy-poverty burdens.

4.2.4. Low-income countries

Tables 10 and 11 report low-income results. KRLS estimates show that climate vulnerability is negatively associated with both SDG and HDI outcomes, confirming that climate stress remains a development constraint where energy poverty and fiscal limits are severe. Emissions growth is positive for the SDG Index but negative for HDI, suggesting that modest emissions may accompany electrification and basic infrastructure while fossil-based expansion can still harm health and living standards (Tumushabe, 2018). Energy productivity is positive and significant for both measures. Renewable shares are negative, consistent with the measurement problem that high renewable use often reflects fuelwood and charcoal rather than modern renewables (Raihan et al., 2026).

The moderation evidence reinforces this interpretation. The negative vulnerability-renewable interaction in KRLS does not imply that modern renewables worsen vulnerability; it suggests that biomass-driven renewable shares may amplify vulnerability through drought exposure, land degradation, and fuel scarcity (Abdallah, 2025). The practical message is that aggregate renewable shares are insufficient in low-income contexts: development gains depend on modern energy access, efficiency, clean cooking, and targeted adaptation.

4.3. Comparing Findings across Income Groups

Income-group comparisons show that transition channels differ by development context. In upper-middle-income countries, energy productivity and modern renewable deployment appear more aligned with development outcomes because these economies have higher electrification, deeper infrastructure, and stronger fiscal capacity (Raihan et al., 2025). In lower-middle-income countries, energy productivity is more dependable than renewable share alone because urbanisation and industrialisation coexist with transmission losses, reliability constraints, and limited long-term finance (Chouksey et al., 2026). In low-income countries, climate vulnerability remains strongly associated with weaker outcomes, while renewable share is harder to interpret because it often reflects traditional biomass rather than modern transition.

A negative or weak renewable-share coefficient should not be read as evidence against renewable energy. It reflects measurement and structure: where biomass dominates, a high renewable share can coincide with low modern energy access, indoor air-pollution burdens, and limited productivity growth (Tiwari et al., 2024; Quan et al., 2025). A development-oriented transition therefore requires reliable electricity access, clean cooking, grids, storage, and productive-use investments so that modern renewables displace costly and polluting fuels rather than coexist with energy poverty. Across groups, the central pattern is that a development-oriented transition is not defined by aggregate renewable shares. It depends on reliable electricity, clean cooking, productive energy use, reduced technical losses, and investments that improve resilience to climate shocks. The subgroup findings support differentiated policy sequencing rather than a uniform transition prescription for all African countries.

4.4. Theoretical Contributions

This study makes five theoretical contributions to research on climate vulnerability, sustainability transitions, and development in Africa. First, it moves beyond treating climate change and green transition indicators as separate direct determinants of development. The moderation framework conceptualises the green transition as a conditioning capacity that can alter the strength of the relationship between climate vulnerability and welfare outcomes. This distinction matters because a transition may expand installed renewable capacity without reducing the exposure of households, firms, and public services to climate shocks. The evidence therefore supports a relational view of transition: its development value depends on whether it changes how climate stress is transmitted into the SDG Index and human development rather than whether a country records a higher renewable share in isolation.

Second, the study distinguishes the quantity of transition from its quality. Sustainability transition research explains long-term

Table 6: Results of machine learning tool – Kernel–based regularized least squares (KRLS) – non–parametric test

Variables	Sustainable development (SDG Index)						Sustainable development (Human Development Index [HDI])					
	(1)	(2)	(3)	(4)	(5)	(6)	(1)	(2)	(3)	(4)	(5)	(6)
cvi	–1.89*** (–9.218)	–0.423*** (–6.800)	–0.389*** (–6.423)	–0.459*** (–7.387)	–0.408*** (–6.324)	–0.396*** (–6.071)	–1.206*** (–8.062)	–0.189*** (–3.088)	–0.167*** (–2.799)	–0.167** (–2.815)	–0.161*** (–2.641)	–0.136** (–2.241)
lcab	–0.057** (–3.332)	0.012** (2.642)	0.001 (1.360)	0.014** (2.931)	0.002*** (3.796)	0.0805 (1.644)	–0.049*** (–3.912)	–0.037*** (7.914)	–0.003*** (8.856)	0.034*** (7.407)	0.004*** (9.754)	0.003*** (6.461)
lerp	0.03*** (5.059)	0.012*** (10.676)	0.011*** (10.127)	0.009*** (12.643)	0.013** (10.556)	0.011*** (9.364)	0.013** (3.373)	0.0115 (1.061)	0.0014 (1.295)	0.033*** (4.524)	0.026** (2.345)	0.0015 (1.385)
lrew	–0.02*** (–3.371)	–0.045*** (–4.821)	–0.004*** (–4.466)	–0.003*** (–3.399)	–0.039*** (–4.146)	–0.029*** (–3.861)	–0.026*** (–6.416)	–0.076*** (–7.602)	–0.006*** (–6.463)	–0.006*** (–6.526)	–0.008*** (–8.482)	–0.006*** (–8.372)
lcab_lerp			0.075*** (7.776)						0.075*** (7.894)			
cvi_lerp				0.012*** (7.045)						0.064*** (3.792)		
lcab_lrew					0.027*** (3.044)						0.029*** (3.426)	
cvi_lrew						0.081*** (5.486)						0.013*** (9.467)
pop		–0.007*** (–5.881)	–0.009*** (–7.236)	–0.007*** (–6.003)	–0.067*** (–5.388)	–0.075*** (–6.070)		–0.002* (–1.810)	–0.027** (–2.389)	–0.0023** (–2.049)	–0.027** (–2.301)	–0.0019* (–1.707)
lace		0.350*** (27.031)	0.349*** (27.805)	0.371*** (27.371)	0.353*** (26.432)	0.358*** (26.668)		0.109*** (8.584)	0.119*** (9.485)	0.127*** (9.767)	0.117*** (9.153)	0.117*** (9.293)
lpse		0.013 (0.868)	0.019 (1.308)	0.019 (1.285)	0.015 (0.912)	0.0239 (1.496)		0.019*** (0.126)	–0.0033 (–0.221)	0.0025 (0.866)	0.0345 (0.225)	0.0064 (0.424)
Obs.	175	175	175	175	175	175	175	175	175	175	175	175
Lambda	0.1059	0.1702	0.1697	0.1431	0.1431	0.1431	0.1037	0.1102	0.1102	0.1102	0.1102	0.1102
Eff. df.	20.99	29.64	29.41	30.45	31.06	30.54	21.09	33.15	32.89	32.56	33.24	32.65
R–squared	0.9555	0.9932	0.993	0.9935	0.9933	0.9934	0.898	0.9809	0.9801	0.9796	0.9793	0.9801
Looloss	1.233	0.2213	0.2275	0.2145	0.2229	0.2228	1.309	0.2962	0.3065	0.3124	0.3164	0.3074
No. of id	7	7	7	7	7	7	7	7	7	7	7	7

t-statistics in parentheses. ***p<0.01, **p<0.05, *p<0.1

Table 7: Results of correlated panels corrected standard errors (PCSEs) – parametric test (robustness analysis)

Variables	Sustainable development (SDG index)						Sustainable development (human development index [HDI])					
	(1)	(2)	(3)	(4)	(5)	(6)	(1)	(2)	(3)	(4)	(5)	(6)
cvi	–0.0306	1.927***	1.552***	3.114***	1.943***	–0.214	0.0946	1.880***	1.412***	1.192**	1.905***	1.652***
	(–0.676)	(6.573)	(5.628)	(5.331)	(6.622)	(–0.514)	(0.310)	(6.569)	(4.913)	(2.302)	(7.074)	(3.541)
lcab	–0.19***	–0.097***	0.508	–0.085***	0.0843	–0.051***	–0.502***	–0.242***	0.160***	–0.313***	0.260***	–0.0192*
	(–13.27)	(–8.121)	(0.907)	(–6.964)	(1.002)	(–3.845)	(–8.274)	(–2.629)	(3.509)	(–3.280)	(4.298)	(–1.811)
lerp	0.20***	0.013***	0.051***	0.206**	0.014***	0.011***	–0.016***	–0.0848**	0.386***	–0.121*	–0.0595	–0.0869**
	(3.518)	(3.473)	(3.579)	(2.575)	(3.562)	(3.237)	(–5.845)	(–2.402)	(3.488)	(–1.763)	(–1.617)	(–2.411)
lrew	–0.33***	–0.042***	–0.036***	–0.034***	–0.0211**	–0.284***	–0.022***	–0.025***	–0.017***	–0.029***	0.00757	–0.0508
	(–3.789)	(–10.79)	(–7.899)	(–7.420)	(–2.040)	(–6.521)	(–4.250)	(–6.868)	(–4.721)	(–7.054)	(0.932)	(–1.336)
lcab_lerp			–0.063***						–0.078***			
			(–2.708)						(–3.930)			
cvi_lerp				0.457**						0.265		
				(2.411)						(1.607)		
lcab_lrew					–0.0356**						–0.056***	
					(–2.192)						(–4.862)	
cvi_lrew						0.632***						0.0673
						(5.696)						(0.680)
Pop		–0.043***	–0.044***	–0.047***	–0.045***	–0.049***		–0.195***	–0.021***	–0.169***	–0.225***	–0.201***
		(–22.05)	(–22.13)	(–16.68)	(–22.02)	(–19.85)		(–12.77)	(–11.61)	(–7.034)	(–17.30)	(–9.829)
lace		0.493***	0.507***	0.404***	0.491***	0.544***		0.289***	0.307***	0.341***	0.287***	0.295***
		(14.83)	(15.08)	(8.474)	(14.61)	(15.90)		(8.786)	(10.31)	(6.307)	(9.338)	(9.250)
lPSE		0.288***	0.246***	0.280***	0.368***	0.156***		–0.016	–0.068***	–0.0119	0.108***	–0.0305
		(8.417)	(7.094)	(8.679)	(7.098)	(3.726)		(–0.662)	(–2.722)	(–0.486)	(2.893)	(–0.920)
Constant	4.95***	2.521***	2.750***	2.114***	2.143***	3.390***	0.782***	–0.942***	–0.657***	–0.706***	–1.534***	–0.849***
	(33.42)	(10.81)	(12.20)	(7.495)	(6.766)	(12.69)	(7.652)	(–4.041)	(–2.716)	(–2.689)	(–6.006)	(–2.916)
Obs.	175	175	175	175	175	175	175	175	175	175	175	175
R-squared	0.269	0.930	0.933	0.932	0.932	0.941	0.263	0.773	0.793	0.775	0.796	0.773
No. of id	7	7	7	7	7	7	7	7	7	7	7	7
Chi-square	496.9	3770	5572	3761	2384	5667	2546	1673	1799	1817	846.7	1756

z-statistics in parentheses. ***p<0.01, **p<0.05, *p<0.1

Table 8: Results of machine learning tool – Kernel–based regularized least squares (KRLS) – non–parametric test

Variables	Sustainable development (SDG index)						Sustainable development (human development index [HDI])					
	(1)	(2)	(3)	(4)	(5)	(6)	(1)	(2)	(3)	(4)	(5)	(6)
cvi	–1.33***	–0.380***	–0.388***	–0.337***	–0.388***	–0.258***	–1.019***	–0.499***	–0.474***	–0.512***	–0.479***	–0.405***
	(–17.365)	(–9.062)	(–9.614)	(–8.535)	(–9.710)	(–7.059)	(–15.197)	(–12.322)	(–11.900)	(–13.451)	(–12.265)	(–11.427)
lcab	–0.022***	–0.017***	–0.013***	–0.016***	–0.013***	–0.015***	–0.003	–0.017***	–0.026***	–0.019**	–0.008	–0.0557
	(–8.841)	(–20.254)	(–21.068)	(–19.563)	(–22.715)	(–19.661)	(1.221)	(–2.112)	(–4.349)	(–2.515)	(–1.465)	(–0.734)
lerp	0.079***	–0.017***	0.028***	0.004**	–0.019***	0.015***	0.054***	0.022***	0.015***	0.022***	0.019***	0.018***
	(9.156)	(–6.520)	(12.092)	(2.026)	(–7.765)	(6.242)	(7.063)	(8.726)	(6.422)	(11.231)	(7.900)	(7.564)
lrew	–0.056***	–0.038***	–0.039***	–0.038***	–0.045***	–0.025***	–0.073***	–0.022***	–0.018***	–0.022***	–0.017***	–0.011***
	(–7.728)	(–13.285)	(–14.945)	(–13.658)	(–18.116)	(–11.506)	(–11.410)	(–7.806)	(–7.175)	(–8.301)	(–6.963)	(–5.004)
lcab_lerp			0.003***						0.008***			
			(14.449)						(4.787)			
cvi_lerp				0.019***						0.078**		
				(–6.453)						(2.775)		
lcab_lrew					0.002***						0.028***	
					(15.210)						(2.708)	
cvi_lrew						0.333***						0.032***
						(–12.545)						(12.654)
pop		–0.014***	–0.014***	–0.014***	–0.014***	–0.015***		–0.0036*	0.042**	0.036*	–0.045**	–0.0031
		(–6.598)	(–6.703)	(–6.741)	(–6.450)	(–7.024)		(–1.711)	(2.045)	(1.780)	(–2.203)	(–1.501)
lace		0.118***	0.109***	0.116***	0.115***	0.114***		0.106***	0.104***	0.108***	0.106***	0.099***
		(16.174)	(15.956)	(16.361)	(16.739)	(16.121)		(14.907)	(15.355)	(15.568)	(15.772)	(14.250)
lPSE		0.141***	0.148***	0.140***	0.149***	0.143***		0.134***	0.158***	0.138***	0.161***	0.158***
		(7.498)	(8.135)	(7.507)	(8.168)	(7.654)		(7.461)	(8.840)	(7.739)	(9.049)	(8.750)
Obs.	500	500	500	500	500	500	500	500	500	500	500	500
Lambda	0.3161	0.2297	0.2796	0.2297	0.2795	0.2795	0.3099	0.2114	0.2613	0.2113	0.2613	0.2613
Eff. df.	26.47	71.78	66.57	69.84	66.03	65.79	26.6	73.53	67.91	71.54	67.37	67.12
R-squared	0.8755	0.9791	0.9767	0.9785	0.9768	0.9763	0.8054	0.9619	0.9553	0.9611	0.9561	0.9558
Looloss	7.911	1.699	1.822	1.713	1.817	1.86	8.643	2.081	2.373	2.115	2.334	2.346
No. of id	20	20	20	20	20	20	20	20	20	20	20	20

t-statistics in parentheses. ***p<0.01, **p<0.05, *p<0.1

Table 9: Results of correlated panels corrected standard errors (PCSEs) – parametric test (robustness analysis)

Variables	Sustainable development (SDG index)						Sustainable development (Human development index [HDI])					
	(1)	(2)	(3)	(4)	(5)	6)	(1)	(2)	(3)	(4)	(5)	(6)
cvi	–1.17***	–0.308***	–0.647***	–1.226***	–0.383***	0.198	–0.763***	–0.624***	–0.767***	–1.076***	–0.601***	–1.064***
	(–20.32)	(–4.674)	(–6.828)	(–5.407)	(–6.138)	(0.688)	(–25.48)	(–15.90)	(–14.07)	(–8.699)	(–15.72)	(–6.614)
lcab	0.0201*	0.014***	–0.031***	0.0107*	0.072***	0.0122**	0.026***	0.0165*	–0.118***	0.0148	–0.0201	0.0018**
	(1.763)	(2.729)	(–6.457)	(1.846)	(5.336)	(2.401)	(2.658)	(1.755)	(–4.781)	(1.627)	(–1.323)	(2.015)
lerp	–0.093**	–0.227***	–0.114***	–0.206***	–0.023***	–0.022***	0.083***	–0.115***	–0.049***	–0.102***	–0.113***	–0.012***
	(–3.243)	(–5.924)	(–10.02)	(–5.732)	(–6.225)	(–6.131)	(2.644)	(–3.505)	(–5.031)	(–4.069)	(–3.465)	(–3.744)
lrew	–0.06***	–0.046***	–0.039***	–0.042***	0.0340**	0.0111	–0.041***	–0.033***	–0.031***	–0.031***	–0.058***	–0.083***
	(–28.49)	(–19.78)	(–14.97)	(–16.95)	(2.209)	(0.335)	(–24.93)	(–17.48)	(–14.36)	(–14.97)	(–3.480)	(–4.851)
lcab_lerp			0.016***						0.067***			
			(7.267)						(4.798)			
cvi_lerp				0.351***						0.173***		
				(4.926)						(3.946)		
lcab_lrew					–0.014***						0.00427	
					(–5.265)						(1.487)	
cvi_lrew						–0.127*						0.111***
						(–1.711)						(2.924)
pop		–0.018***	–0.0022*	–0.014***	–0.019***	–0.018***		0.019***	0.024***	0.217***	0.019***	0.197***
		(–4.195)	(–1.738)	(–2.860)	(–4.584)	(–4.426)		(5.307)	(5.650)	(5.549)	(5.483)	(5.426)
lace		0.143***	0.130***	0.142***	0.141***	0.140***		0.092***	0.087***	0.092***	0.093***	0.096***
		(17.19)	(16.32)	(17.38)	(18.06)	(19.02)		(15.12)	(13.79)	(14.98)	(14.57)	(14.15)
lPSE		0.294***	0.245***	0.285***	0.284***	0.288***		0.326***	0.305***	0.322***	0.329***	0.331***
		(7.022)	(6.034)	(6.759)	(6.745)	(6.727)		(9.380)	(9.053)	(9.304)	(9.301)	(9.159)
Constant	5.54***	3.799***	4.328***	4.293***	3.455***	3.597***	1.068***	0.128	0.350***	0.371***	0.235**	0.303***
	(446.0)	(29.07)	(28.35)	(23.48)	(24.49)	(24.43)	(162.2)	(1.542)	(4.004)	(3.914)	(2.174)	(3.537)
Obs.	500	500	500	500	500	500	500	500	500	500	500	500
R-squared	0.681	0.795	0.812	0.800	0.799	0.796	0.644	0.795	0.801	0.797	0.795	0.796
No. of id	20	20	20	20	20	20	20	20	20	20	20	20
Chi-square	19032	18266	31948	24881	29277	17250	8557	23549	24442	23726	20111	22891

z–statistics in parentheses. ***p<0.01, **p<0.05, *p<0.1

Table 10: Results of machine learning tool – Kernel–based regularized least squares (KRLS) – non–parametric test

Variables	Sustainable development (SDG Index)						Sustainable development (Human Development Index [HDI])					
	(1)	(2)	(3)	(4)	(5)	(6)	(1)	(2)	(3)	(4)	(5)	(6)
lcab	0.014***	0.096***	0.054***	0.094***	0.067***	0.093***	–0.082***	–0.046***	–0.051***	–0.042***	–0.022***	–0.043***
	(4.951)	(7.763)	(5.749)	(8.108)	(9.009)	(8.197)	(–4.422)	(–7.142)	(–10.289)	(–6.981)	(–5.714)	(–7.364)
cvi	–1.390***	–0.429***	–0.319***	–0.417***	–0.388***	–0.197***	–0.619***	–0.133***	–0.087***	–0.152***	–0.095**	–0.051***
	(–15.410)	(–8.599)	(–6.845)	(–8.926)	(–8.405)	(–6.351)	(–10.465)	(–5.135)	(–3.579)	(–6.283)	(–3.967)	(–3.199)
lerp	0.154***	0.036***	–0.016***	0.034***	0.031***	0.034***	0.137***	0.029***	0.023***	0.021***	0.026***	0.024***
	(12.939)	(9.469)	(4.907)	(12.122)	(9.035)	(10.237)	(17.568)	(14.637)	(13.518)	(14.746)	(14.588)	(14.365)
lrew	–0.0349	–0.078***	–0.069***	–0.091***	–0.081***	–0.070***	–0.071**	–0.059***	–0.058***	–0.062***	–0.058***	–0.055***
	(–0.960)	(–5.181)	(–5.021)	(–6.415)	(–5.738)	(–5.121)	(–2.976)	(–7.503)	(–7.996)	(–8.408)	(–8.009)	(–7.813)
lcab_lerp			0.029***						0.057***			
			(12.659)						(4.757)			
cvi_lerp				0.023***						0.027***		
				(5.911)						(13.570)		
lcab_lrew					0.012***						0.043***	
					(8.087)						(–5.584)	
cvi_lrew						–0.049***						–0.024***
						(–10.560)						(–9.781)
pop		–0.024***	–0.022***	–0.021***	–0.021***	–0.021***		–0.0602	–0.0425	–0.0493	–0.047	–0.0765
		(–6.487)	(–5.979)	(–5.664)	(–5.695)	(–5.696)		(–0.792)	(–0.319)	(–0.254)	(–0.804)	(–0.410)
lace		0.043***	0.043***	0.041***	0.043***	0.044***		0.057***	0.057***	0.055***	0.059***	0.059***
		(7.130)	(7.411)	(6.817)	(7.375)	(7.695)		(18.158)	(18.873)	(17.863)	(19.578)	(19.944)
lPSE		0.198***	0.210***	0.206***	0.208***	0.197***		0.167***	0.178***	0.177***	0.176***	0.173***
		(13.955)	(15.739)	(15.186)	(15.308)	(15.072)		(22.554)	(25.602)	(25.207)	(25.003)	(25.603)
Obs.	400	400	400	400	400	400	400	400	400	400	400	400
Lambda	0.2585	0.1647	0.2147	0.2147	0.2147	0.2148	0.2552	0.1647	0.2238	0.2237	0.2237	0.2239
Eff. df.	33.73	74.59	69.29	67.07	68.68	68.32	33.83	74.59	68.47	66.26	67.86	67.49
R–squared	0.7926	0.9655	0.9603	0.9591	0.9599	0.9611	0.7827	0.977	0.9729	0.9722	0.9728	0.9736
Looloss	10.1	2.156	2.557	2.411	2.500	2.300	6.535	0.9383	1.064	1.058	1.063	1.023
No. of id	16	16	16	16	16	16	16	16	16	16	16	16

t-statistics in parentheses. *** P<0.01, ** P<0.05, * P<0.1

Table 11: Results of correlated panels corrected standard errors (PCSEs) – Parametric Test

Variables	Sustainable development (SDG index)						Sustainable development (Human Development Index [HDI])					
	(1)	(2)	(3)	(4)	(5)	(6)	(1)	(2)	(3)	(4)	(5)	(6)
cvi	–1.16***	–0.728***	–0.703***	3.294***	–0.633***	–4.728**	–0.495***	0.0944**	0.0836**	1.190***	0.0432	2.976**
	(–15.70)	(–15.15)	(–13.74)	(9.746)	(–11.13)	(–2.443)	(–7.957)	(2.477)	(2.166)	(10.90)	(1.206)	(2.019)
Lcab	0.09***	0.0233*	0.0143*	0.00164	0.429***	0.00259*	0.032***	–0.039***	–0.092***	–0.040***	–0.234***	–0.040***
	(5.983)	(1.660)	(1.875)	(1.250)	(6.511)	(1.803)	(2.772)	(–6.550)	(–5.577)	(–6.933)	(–4.268)	(–6.768)
lerp	–0.33***	–0.025***	–0.0602	0.880***	–0.027***	–0.024***	–0.017***	–0.0255	–0.013***	0.244***	–0.00144	–0.00381*
	(–6.132)	(–7.321)	(–0.0374)	(12.68)	(–8.552)	(–6.861)	(–4.229)	(–1.338)	(–3.627)	(11.56)	(–0.779)	(–1.750)
lrew	–0.09***	–0.071***	–0.075***	–0.201***	0.460***	–0.516**	–0.082***	–0.092***	–0.090***	–0.127***	–0.377***	0.229
	(–4.579)	(–4.011)	(–3.993)	(–11.19)	(6.013)	(–2.338)	(–5.764)	(–9.311)	(–9.339)	(–11.08)	(–5.579)	(1.387)
lcab_lerp			–0.0483						0.021***			
			(–1.481)						(3.339)			
cvi_lerp				–1.524***						–0.415***		
				(–12.67)						(–11.25)		
lcab_lrew					–0.081***						0.044***	
					(–6.421)						(4.188)	
cvi_lrew						0.789**						–0.568**
						(2.070)						(–1.973)
pop		0.027***	0.028***	0.031***	0.248***	0.027***		–0.050***	–0.055***	–0.0374**	–0.0392**	–0.0482**
		(3.665)	(3.704)	(4.848)	(3.452)	(3.624)		(–2.593)	(–2.911)	(–2.292)	(–2.135)	(–2.521)
lace		0.094***	0.094***	0.059***	0.095***	0.093***		0.088***	0.089***	0.079***	0.088***	0.089***
		(8.943)	(8.505)	(4.952)	(9.176)	(8.631)		(13.59)	(14.26)	(11.76)	(12.82)	(13.40)
lPSE		0.262***	0.267***	0.306***	0.281***	0.263***		0.311***	0.309***	0.323***	0.301***	0.310***
		(12.30)	(11.83)	(16.56)	(11.47)	(12.20)		(21.84)	(22.11)	(21.86)	(26.37)	(22.56)
Constant	5.76***	4.685***	4.590***	2.620***	1.913***	6.885***	1.154***	–0.147***	–0.105**	–0.709***	1.345***	–1.731**
	(45.46)	(50.33)	(43.31)	(14.18)	(4.418)	(6.325)	(14.13)	(–3.220)	(–2.187)	(–9.521)	(3.924)	(–2.125)
Obs.	400	400	400	400	400	400	400	400	400	400	400	400
R-squared	0.418	0.640	0.644	0.748	0.652	0.641	0.237	0.797	0.799	0.817	0.806	0.798
No. of id	16	16	16	16	16	16	16	16	16	16	16	16
Chi-square	1136	2028	2913	4706	1578	2471	2279	2298	3157	2725	2866	2221

z-statistics in parentheses. *** P<0.01, ** P<0.05, * P<0.1

changes in technologies, institutions, infrastructure, and user practices, rather than technology substitution alone (Markard et al., 2012). The separation of energy productivity from renewable energy share applies this insight to African energy systems. Energy productivity captures the capacity to convert energy into output and public welfare, while the renewable share may combine modern electricity sources with traditional biomass. The findings show why these indicators cannot be treated as interchangeable measures of greenness. A high renewable share can coexist with low electricity access, unreliable supply, indoor air pollution, and weak productive use. The study therefore advances the concept of transition quality, defined here by the extent to which energy system change improves efficiency, reliability, modern access, and resilience.

Third, the use of the SDG Index and the Human Development Index connects sustainability transition analysis to a capability-based understanding of development. In this perspective, development concerns the substantive opportunities that people possess, not output growth alone (Sen, 1999). The consistently positive associations of electricity access and primary school enrolment with both development measures indicate that the climate and energy nexus operates through basic capabilities, including education, health, mobility, communication, and access to productive services. This shifts the theoretical benchmark for judging an energy transition from carbon intensity or renewable deployment alone to its capacity to preserve and expand human capabilities under climate stress.

Fourth, the income group results add a contextual proposition to transition theory. The same transition indicator can have different development meanings because countries differ in grid maturity, fiscal capacity, industrial structure, clean cooking access, and institutional ability to manage investment. Energy productivity is more consistently aligned with development in low and lower middle-income settings, whereas the effect of renewable shares depends more strongly on whether modern technologies displace traditional biomass and unreliable fuels. The findings therefore reject a uniform transition pathway for African economies and support a complementarity argument: renewable technologies generate broader development gains when they are combined with networks, storage, skills, finance, social protection, and capable public institutions.

Finally, the study brings distributional and recognition concerns into the climate transition and development relationship. Energy justice and just transition scholarship emphasise who receives reliable energy, who bears adjustment costs, and whose needs are recognised in policy design (Jenkins et al., 2016; Newell and Mulvaney, 2013). The results are consistent with this perspective because energy access is strongly associated with development, while aggregate renewable shares are not uniformly beneficial. The theoretical implication is not that renewable energy reduces development, but that transition indicators have limited explanatory value when they omit access, affordability, reliability, and the social distribution of benefits and costs. These propositions are associational rather than causal, but they provide a clearer framework for future tests of when green transition policies reduce the development penalty associated with climate vulnerability.

5. PRACTICAL RELEVANCE FOR POLICYMAKERS

The results provide a practical basis for redesigning African green transition strategies around development performance. Governments should not assess progress mainly through the percentage of renewable energy in final consumption. That measure can rise because households remain dependent on fuelwood and charcoal, even when electricity access, reliability, and clean cooking conditions remain poor. National transition scorecards should therefore separate modern renewable electricity from traditional biomass and report energy productivity, grid reliability, technical and commercial losses, clean cooking access, affordability, and the continuity of electricity supplied to firms, schools, health facilities, and water systems. Linking these indicators to SDG and human development outcomes would make transition policy more accountable to welfare rather than installed capacity alone.

Policy sequencing should reflect the different constraints identified across income groups. In low-income countries, the immediate priorities are modern electricity access, clean cooking, climate resilient decentralised systems, and protection of essential public services. Grants and highly concessional finance are more appropriate for these investments than debt creating projects that depend on rapid tariff increases. Distributed solar, mini grids, storage, and clean cooking programmes should be designed around productive uses such as irrigation, agro processing, cold storage, digital services, and local enterprises. These uses raise the development return from each unit of energy and are more consistent with the positive role of energy productivity in the estimates.

Lower middle-income countries require a different emphasis. Their policy problem is not only connection, but the capacity of expanding energy systems to support urbanisation and industrialisation without large reliability losses, pollution burdens, or fiscal stress. Priority measures include transmission and distribution upgrades, reduction of system losses, energy efficiency standards for buildings and industry, competitive procurement of generation and storage, and finance for firms that adopt efficient equipment. Climate adaptation should also be integrated into power, transport, water, and urban investment appraisal because climate vulnerability weakens both SDG and human development outcomes in this group.

Upper middle-income countries can place greater weight on system integration, storage, demand management, industrial decarbonisation, and the retirement or repurposing of high carbon assets. However, the estimates for this group are based on only seven countries and should not be used as a uniform prescription. Country level planning should identify regions, workers, and consumers that may bear transition costs. Reskilling, local economic diversification, and negotiated adjustment support are needed where fossil fuel industries or energy intensive activities are regionally concentrated. This follows the just transition principle that decarbonisation should address distributional, procedural, and recognition concerns rather than transfer costs to groups with the least capacity to absorb them (Jenkins et al., 2016; Newell and Mulvaney, 2013).

Energy price reform also requires careful sequencing. Removing poorly targeted subsidies can improve fiscal efficiency, but abrupt price increases can reduce energy access and weaken household welfare. Reform packages should combine transparent tariff adjustment with lifeline tariffs, targeted cash transfers, support for clean cooking conversion, and temporary assistance for vulnerable firms and households. The relevant policy test is whether the reform improves reliable service and energy productivity without increasing energy poverty. This is especially important because the empirical results show that electricity access remains one of the most stable correlates of both development outcomes.

Climate finance institutions and national development banks should use the same development test. Project selection should favour investments that jointly reduce climate exposure, improve energy productivity, and expand reliable modern energy. Funding conditions require measurable service outcomes, including hours of reliable supply, reduced network losses, new clean cooking users, lower energy costs per unit of output, and improved service continuity in climate exposed communities. Ministries responsible for finance, energy, environment, education, health, industry, and social protection should share these indicators so that transition policies are not implemented as a narrow electricity sector programme.

The central policy message is therefore one of differentiation and discipline. African countries need more modern renewable energy, but renewable deployment should be treated as an input rather than the final objective. The objective is to create a resilient energy system that raises productivity, protects basic capabilities, and reduces the welfare consequences of climate vulnerability. Policies that do not improve access, reliability, affordability, and productive use may change the energy mix without producing a comparable improvement in sustainable development.

6. CONCLUSIONS, LIMITATIONS, AND DIRECTIONS FOR FUTURE RESEARCH

This study examined whether green transition indicators moderate the relationship between climate stress and sustainable development in 43 African countries from 2000 to 2024. Climate vulnerability is consistently associated with weaker SDG Index and Human Development Index outcomes. Energy productivity is the more dependable transition channel, while renewable energy shares have mixed associations because they do not distinguish modern renewable energy from traditional biomass. The income group estimates further show that the development relevance of transition indicators depends on energy access, infrastructure, fiscal capacity, and the structure of national energy systems. Taken together, the results indicate that a green transition reduces the welfare costs of climate vulnerability when it improves reliable modern energy, productive energy use, affordability, and resilience.

The findings should be interpreted in light of several limitations. Index based measures embed in measurement choices and do not fully capture within country inequality. The renewable energy variable does not separate traditional biomass from modern renewable sources, and the upper middle-income subgroup contains only seven countries. In addition, the observational design, nonstationarity, and cross-sectional dependence mean that the estimates represent long run conditional associations rather than definitive causal effects. Future research should use disaggregated renewable indicators, measures of grid reliability and energy affordability, clean cooking data, and subnational evidence. Research designs that exploit policy changes, infrastructure rollout, or climate shocks would also help identify the mechanisms through which transition investments affect employment, productivity, public services, and household welfare.

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APPENDIX

Appendix A : List of 43 Selected African Countries based on 2025 World Bank income classification

Group	Countries
Low income countries (16)	Burkina Faso, Burundi, Central African Republic, Chad, Congo, DR., Ethiopia, Gambia, Guinea-Bissau, Madagascar, Malawi, Mali, Mozambique, Niger, Rwanda, Sudan, Uganda
Lower-middle income (20)	Angola, Benin, Cameroon, Comoros, Congo, Cote d'Ivoire, Egypt, Ghana, Guinea, Kenya, Lesotho, Mauritania, Morocco, Namibia, Nigeria, Senegal, Tanzania, Tunisia, Zambia, Zimbabwe
Upper-middle income (7)	Algeria, Botswana, Cabo Verde, Equatorial Guinea, Gabon, Mauritius, South Africa