PROBLEMY EKOROZWOJU/ PROBLEMS OF SUSTAINABLE DEVELOPMENT

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Carbon Emission, Human Capital and Adoption of Green Energy Technology in Sub- Saharan Africa

Emisja dwutlenku węgla, kapitał ludzki i wdrażanie technologii zielonej energii w Afryce Subsaharyjskiej

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Abstract

In this paper, we examine the relationship among human capital, carbon emissions, and the adoption of green energy technology. The study engaged 39 countries from Sub-Saharan African (SSA) for the period 2000 - 2022. We made use of panel data approach that handles cross-sectional dependence and heterogeneity – including Cross-Sectionally Augmented Distributed Lag (CS-DL), Cross-Sectionally Augmented ARDL (CS-ARDL), and Fixed-effect regression with Driscoll-Kraay standard errors. Results from the study show that carbon emissions have a significant negative impact on renewable energy adoption, proving that ecological dilapidation could induce green energy transitions. For SDG-15, mean years of schooling appears to significantly slow down the progress toward achieving the goal, possibly due to construction of schools. While regulatory quality improves the progress toward achieving SDG-15 in East Africa; the regulation hinders the progress in Southern Africa, perhaps due to land crisis in the region. Pre COVID results suggest that mean years of schooling have positive and significant effects on both renewable energy adoption and SDG-15 progress; but the finding reversed in the post-COVID. Lastly, carbon emission has negative and significant effect on both sustainability indicators in the pre-COVID but appear insignificant in the post-COVID. The study contributes directly to the achievement of Sustainable Development Goals (SDGs), specifically, SDG-7 Affordable and clean energy and SDG-13 Mitigation of climate change by highlighting the need for clean energy adoption, climate-resilient policy frameworks, and the critical role of education in sustainable energy transitions. The findings emphasize the essence of integrated policy efforts that strengthen human capital and regulatory frameworks to support low-carbon transitions across SSA, with context-specific approaches contingent on sub-regional variations. By integrating indicators related to SDG 4 (quality education), SDG-7 (affordable and clean energy), SDG-13 (climate action) and SDG-15 (life on land), this study provides a multi-goal perspective on sustainable energy transitions in Sub-Saharan Africa.

Key words: green energy technology, carbon emissions, human capital, renewable energy adoption, sustainable development

Streszczenie

W niniejszym artykule analizujemy związek między kapitałem ludzkim, emisjami dwutlenku węgla a wdrażaniem technologii zielonej energii. W badaniu wzięło udział 39 krajów Afryki Subsaharyjskiej (SSA) w latach 2000–2022. Wykorzystaliśmy podejście oparte na danych panelowych, które uwzględnia przekrojową zależność i heterogeniczność – w tym Cross-Sectionally Augmented Distributed Lag (CS-DL), Cross-Sectionally Augmented ARDL (CS-ARDL) oraz regresję o efekcie stałym z błędami standardowymi Driscolla-Kraaya. Wyniki badania pokazują, że emisje dwutlenku węgla mają istotny negatywny wpływ na wdrażanie energii odnawialnej, udowadniając, że degradacja środowiska może prowadzić do rozwoju zielonej energii. W przypadku Celu Zrównoważonego Rozwoju nr 15, średni czas nauki wydaje się znacząco spowalniać postęp w realizacji tego celu, prawdopodobnie ze względu na budowę szkół. Podczas gdy jakość regulacji prawnych poprawia postęp w realizacji Celu Zrównoważonego Rozwoju nr 15 w Afryce Wschodniej, regulacje prawne hamują postęp w Afryce Południowej, prawdopodobnie ze względu na kryzys gruntowy w tym regionie. Wyniki sprzed pandemii COVID sugerują, że średnia liczba lat nauki ma pozytywny i istotny wpływ zarówno na wdrażanie energii odnawialnej, jak i postęp w realizacji SDG-15; jednak odchylenie to uległo odwróceniu po pandemii COVID. Wreszcie, emisja dwutlenku węgla ma negatywny i istotny wpływ na oba wskaźniki zrównoważonego rozwoju przed pandemią COVID, ale wydaje się nieistotna po jej zakończeniu. Badanie przyczynia się bezpośrednio do osiągnięcia Celów Zrównoważonego Rozwoju (SDG), a konkretnie SDG-7 Przystępna i czysta energia oraz SDG-13 Działania na rzecz klimatu, podkreślając potrzebę wdrażania czystej energii, odpornych na zmiany klimatu ram polityki oraz kluczową rolę edukacji w zrównoważonych transformacjach energetycznych. Odkrycia podkreślają istotę zintegrowanych działań politycznych, które wzmacniają kapitał ludzki i ramy regulacyjne w celu wspierania transformacji niskoemisyjnych w całym regionie Afryki Subsaharyjskiej, przy czym podejścia specyficzne dla danego kontekstu zależą od różnic subregionalnych. Dzięki zintegrowaniu wskaźników odnoszących się do Celu Zrównoważonego Rozwoju 4 (jakość edukacji), Celu Zrównoważonego Rozwoju 7 (przystępna i czysta energia), Celu Zrównoważonego Rozwoju 13 (działania na rzecz klimatu) i Celu Zrównoważonego Rozwoju 15 (życie na lądzie), badanie to przedstawia wielocelową perspektywę zrównoważonych transformacji energetycznych w Afryce Subsaharyjskiej.

Słowa kluczowe: zielona technologia energetyczna, emisja dwutlenku węgla, kapitał ludzki, wdrażanie odnawialnych źródeł energii, zrównoważony rozwój

Introduction

The global energy landscape is experiencing a significant revolution, driven by the pressing need to mitigate climate change, reduce carbon emissions, and transition towards cleaner and more sustainable energy systems. This shift is not only a technological challenge but also a socio-economic and policy imperative. As climate-related disasters escalate and fossil fuel dependence becomes increasingly unsustainable, countries around the world are pursuing various strategies to accelerate the adoption of green energy technologies. Nowhere is this transformation more critical and potentially impactful than in Sub-Saharan Africa (SSA), a region characterized by vast renewable energy potential, low per capita energy access, and high vulnerability to climate change (He et al., 2024; Li et al., 2024).

Over the past two decades, Sub-Saharan African countries have made notable efforts to reform their energy sectors. These include renewable energy policies, electricity market deregulation, public-private partnerships, and investments in off-grid solutions (Onabote et al., 2021). Despite these initiatives, green energy adoption across the region remains uneven and slower than in other parts of the world. While some countries like Kenya and Ethiopia have made significant investments in geothermal and wind power, others rely heavily on fossil fuels, particularly coal and oil. This uneven progress raises essential questions about the key drivers and constraints shaping green energy adoption in SSA.

This research is conceptually anchored within the Sustainable Development Goals (SDGs). Specifically, three SDGs are directly operationalized through the study variables: **SDG 7** (Affordable and Clean Energy) represented by the renewable energy adoption rate; **SDG 4** (Quality Education) captured by mean years of schooling as a proxy for human capital; and **SDG 13** (Climate Action) proxied by carbon dioxide emissions per capita. These variables jointly influence **SDG 15** (Life on Land), which reflects environmental sustainability outcomes. Thus, the model simultaneously mirrors multiple SDG interactions, emphasizing the interdependence between education, clean energy access, climate response, and terrestrial ecosystem health in SSA.

A central concern in this context is the role of carbon emissions. Although SSA countries collectively contribute a relatively small share to global carbon emissions, the rate of increase in emissions from fossil fuel combustion and land-use change is accelerating (Adeleye et al., 2021). Ironically, many of these countries are among the most climate-vulnerable globally. Rising temperatures, erratic rainfall patterns, droughts, and floods are already disrupting food and energy systems. These environmental stressors simultaneously pose a challenge and present an opportunity – on one hand, highlighting the urgent need for mitigation, and on the other, creating the impetus for cleaner energy investments (Osabohien et al., 2025).

Closely linked to carbon emissions is the importance of human capital. As energy systems become more technologically advanced, the relevance of education and skills development becomes even more pronounced. The deployment and maintenance of renewable energy infrastructure require skilled professionals – engineers, technicians, analysts, and policy designers. In this regard, educational attainment, measured by indicators such as mean years of schooling, emerges as a critical enabler of green transitions (Özbay & Duyar, 2022; Olopade et al., 2020). Higher levels of education can foster awareness of environmental issues, promote behavioral change, and improve societal receptiveness to renewable energy technologies.

However, while carbon emissions and education are widely recognized as relevant variables in energy transition discourse, the empirical literature on their interaction in SSA remains limited. Many existing studies focus on individual countries or examine these variables in isolation, without considering their joint effect or accounting for regional heterogeneity. For instance, while Olanrele and Fuinhas (2021) assess renewable electricity adoption in SSA, they do not incorporate education or regulatory quality into their framework. Similarly, Adewuyi and

Awodumi (2017) examine energy-growth-emissions linkages, but do not focus specifically on green energy adoption. Furthermore, most studies adopt first-generation econometric methods that may overlook important statistical issues such as cross-sectional dependence and unobserved heterogeneity, thereby limiting the generalizability of their findings.

To bridge this gap, the current study investigates the interrelationships between carbon emissions, human capital, and the adoption of green energy technology using panel data from 39 SSA countries covering the period 2000–2022. The study employs robust second-generation panel econometric techniques including the Cross-Sectionally Augmented Distributed Lag (CS-DL) model, Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) model, and the Feasible Generalized Least Squares (FGLS) estimator. These models account for cross-sectional dependence, regional spillovers, and both short- and long-run effects, thereby enhancing the reliability of the results (Chudik & Pesaran, 2015; Chudik et al., 2016).

The theoretical foundation of this research is rooted in both demand- and supply-side energy transition dynamics. On the demand side, rising carbon emissions and deteriorating environmental conditions may prompt governments, firms, and households to adopt cleaner energy alternatives. This aligns with the environmental Kuznets curve (EKC) hypothesis, which posits that emissions rise with income to a certain point, after which cleaner technologies are adopted (Mohamed et al., 2024). On the supply side, human capital facilitates the adoption and diffusion of green technologies. Educated populations are more likely to understand the benefits of renewables, assimilate technical information, and support green policy initiatives (Özbay & Duyar, 2022).

Methodologically, this study makes several contributions to the literature. First, it focuses on SSA – a region with unique socio-economic and institutional characteristics often neglected in global energy studies. Second, it utilizes multi-method approaches to address data limitations, endogeneity concerns, and the need to model heterogeneity and structural dependencies. Third, the analysis is disaggregated by sub-regions (Central, East, South, and West Africa), revealing important geographic differences in energy transitions. This regional lens is crucial for policymakers given the diverse energy mixes and policy environments across SSA.

Moreover, this research contributes to the global agenda of the United Nations Sustainable Development Goals (SDGs), especially SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action), and SDG 4 (Quality Education). By identifying how education and emissions interact to shape renewable energy uptake, the study reinforces SDG Target 7.2, which emphasizes increasing the share of renewables in the global energy mix. Similarly, the results support SDG Target 13.2, advocating the integration of climate measures into national strategies. On the education front, the study aligns with SDG Target 4.4, which calls for enhancing skills relevant to sustainable development and clean technologies.

This study is timely given the ongoing global push for just energy transitions and green recovery post-COVID-19. As countries in SSA revise their Nationally Determined Contributions (NDCs) under the Paris Agreement and seek green investment flows, evidence-based policymaking becomes paramount. The study sheds light on systemic challenges such as weak regulatory quality (Degbedji et al., 2024), carbon lock-in (Osabohien et al., 2025), and fossil fuel dependency – factors that must be tackled through multi-stakeholder approaches. It also reflects on how fossil fuel subsidies discourage renewable energy adoption (Adewuyi & Awodumi, 2017), and how regulatory frameworks can either facilitate or hinder the energy transition (Imandojemu et al., 2025).

Therefore, the primary objectives of this study are: (i) to investigate the effect of carbon emissions on the adoption of green energy technology; (ii) to evaluate the impact of human capital on renewable energy uptake; and (iii) to identify regional differences and institutional moderators that influence the pace and direction of energy transitions. These objectives are pursued using a comprehensive dataset drawn from reputable sources such as the World Bank's World Development Indicators (WDI), the UNDP Human Development Reports, and the Worldwide Governance Indicators (WGI).

2. Data and methodology

2.1. Model specification and estimation techniques

This study examines the role of human capital and carbon emission in adoption of green energy technology. Several factors come into interplay to determine the adoption and, these factors include cost savings or environmental benefits, user-friendliness of the technology, government environmental policies, among other things. For instance, Özbay and Duyar (2022) establish that level of education makes it easier for people to adopt technology. Another channel through which education promotes technology acceptance is through job opportunities. Sophisticated technology requires high skilled labor to operate and maintain it.

Level of carbon emission could necessitate countries to incentivize the adoption of green technology. Equation (1) specifies the relationship between adoption of green energy technology and the explanatory variables: Equation (1) therefore represents an empirical SDG interaction framework, where GETC → SDG 7, EDUL → SDG 4, CO_2 → SDG 13, and SDG-15 serves as the composite environmental outcome variable.

$$GETC_{it} = \delta_0 + \delta_1 EDUL_{it} + \delta_2 CO2P_{it} + \delta_3 RGDP_{it} + \delta_4 REGQ_{it} + \mu_{it} \quad (1)$$

Where $GETC_{it}$ stands for adoption of green energy technology and SDG-15; $EDUL_{it}$ is level of education, proxied by mean years of schooling and; $CO2P_{it}$ is the carbon emission per capita at time *t* in country *i*. $RGDP_{it}$, $REGQ_{it}$ and μ_{it} refer to real GDP, regulatory quality and error term respectively, all at time *t* in country *i*.

2.2. Data and Estimation Techniques

This study utilizes annual panel data for the period 2000-2022 for 39 Sub-Saharan African (SSA) countries[1] to explore the effects of carbon emission and human capital on adoption of green energy technology and SDG-15 in the region. The countries are proportionately drawn from all the sub-regions. Data for carbon emission, adoption of green energy technology and real GDP are extracted from World Development Indicators (WDI). Data for mean years of schooling is sourced from United Nations' Development Program (UNDP) database while Worldwide Governance Indicators (WGI) remains the source of data on regulatory quality and data on SDG-15 from Sustainable Development Report (SDR). Table 1 presents the definitions and measurements of the variables as well as sources of data.

Table 1. Definitions and measurements of variables

Variables	Measurements	Sources
Green Energy Technology	The proportion of energy derived from renewable sources (e.g., solar, wind, hydro, geothermal) in a country's total energy consumption. Renewable energy consumption (% of total final energy consumption)	WDI
Mean Years of Schooling	Average number of years of formal education completed by individuals aged 25 and older.	UNDP
Real GDP	Gross Domestic Product adjusted for inflation, GDP at constant prices in US Dollars.	WDI
CO_2 per-capita	Total carbon dioxide emissions metric tons produced by fossil fuel combustion and industrial processes, divided by the population.	WDI
Regulatory Quality	The ability of governments to formulate and implement sound policies and regulations that permit and promote private sector development. Standardized score ranging from -2.5 (weak) to +2.5 (strong).	WGI
SDG-15	SDG-15: Life on Land focuses on protecting, restoring and promoting sustainable use of terrestrial ecosystems. The SDG-15 index is a composite score showing the extent to which a country progresses toward achieving the goal. It is scaled from 0 to 100—where 100 represents full achievement of all underlying targets.	SDR

Note: World Development Indicators (WDI), Worldwide Governance Indicators (WGI) and United Nations' Development Programme (UNDP).

Given the likelihood of spillover effects and economic interdependence among SSA countries, we begin by testing for cross-sectional dependence using the Pesaran's (2004) Cross-Sectional Dependence (CD) test. Detecting cross-sectional dependence informs the choice of second-generation panel data methods. Table 2 indicates strong evidence of cross-sectional dependence in the data for all the variables. Hence, the countries in the dataset are interconnected through shared policies, trade, or regional influences, and shocks or trends in one country can spill over to others. The presence of cross section dependence necessitates the use of second-generation panel unit root tests. Equation (2) specifies

$$CD = \sqrt{\frac{2}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\sqrt{T_{ij}\hat{\rho}_{ij}}\right) \tag{2}$$

Where ρ_{ij} is a product-moment form of correlation coefficient of the errors, *N* is the total number of observation and *T* is the time.

The decision to divide the analysis into pre- and post-COVID-19 periods was guided by both conceptual relevance and data availability. The COVID-19 pandemic caused unprecedented structural disruptions that affected global energy supply chains, labor mobility, and public-sector investment priorities across Sub-Saharan Africa. These shifts had profound implications for renewable-energy deployment and environmental governance, warranting a distinct temporal comparison. However, reliable data for the COVID-19 period (2020–2022) are limited in most international databases – particularly WDI, UNDP, and WGI – making a three-phase division (pre-, during-, and post-COVID) statistically infeasible.

[1]Angola, Benin, Botswana, Burkina Faso, Burundi, Cabo Verde, Cameroon, Central African Republic, Chad, Comoros, Democratic Republic of Congo, Congo Republic, Cote d'Ivoire, Equatorial Guinea, Eswatini, Gabon, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritius, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Seychelles, Sierra Leone, South Africa, Tanzania, Togo, Uganda, & Zambia.

Therefore, the study employs a two-phase structure – pre-COVID (2000–2019) and COVID (2020–2022) which effectively captures the pandemic's immediate and lagged effects without compromising sample balance. This design follows established approaches in energy and environmental economics that treat the pandemic as a major exogenous shock influencing emission dynamics, renewable adoption, and institutional responses (Osabohien et al., 2025; Yin et al., 2022; Mohamed et al., 2024). The segmentation enables the analysis to isolate how post-pandemic recovery efforts and fiscal stimuli have shaped the region's progress toward the Sustainable Development Goals (SDGs), especially those related to clean energy (SDG 7), climate action (SDG 13), and education (SDG 4).

Table 2. Cross Section Dependence Test

Variables	Pesaran CD Statistics	Prob. Value
Green Energy Technology	41.03***	0.000
SDG15	19.69***	0.000
Mean Years of Schooling	54.80***	0.000
Real GDP	115.72***	0.000
CO_2	84.56***	0.000
Regulatory Quality	9.57***	0.000

*** shows the significance level at 1%.

To ensure the stationarity of the series and avoid spurious regression, we apply second-generation panel unit root tests that account for cross-sectional dependence: Cross-Sectionally Augmented Dickey-Fuller (CADF) and Cross-sectionally Augmented IPS (CIPS) tests, developed by Pesaran (2007). These tests provide robust evidence on the integration properties of the variables. The CADF test extends the ADF by incorporating cross-sectional averages to proxy unobserved common factors. The CIPS statistic aggregates results from individual CADF regressions to address cross-section dependence. Equation (3) summarizes the relationship or difference between CADF and CIPS (3):

$$CADF = \tau_i(N,T_i) \text{ and } CIPS = \frac{1}{N}\sum_{i=1}^{N}\tau_i(N,T_i)\text{ , then } CIPS = \frac{1}{N}\sum_{i=1}^{N} CADF_i \quad (3)$$

Where τ_i is a parameter controlling for cross-section dependence in the test and CADF is appropriate for unbalanced panel data. If variables are found to be integrated of the order one I(1) or zero I(0), we proceed to examine long-run relationships using: Pedroni (1999) and Westerlund (2007) panel co-integration tests. Pedroni (1999, 2004) introduced residual-based tests to detect cointegration in heterogeneous panels. The framework allows for cross-sectional dependence and heterogeneity in slopes and error variances. The framework is flexible for panels with moderate number of observations. It is robust to structural breaks if trends are included. Westerlund propounded error-correction-based tests that directly estimate the speed of adjustment to equilibrium, avoiding reliance on residual stationarity. Westerlund test has higher power than residual-based tests in small T. It models short-run dynamics and long-run equilibrium.

Having established long-run relationships between the variables, we employ Cross-Sectionally Augmented Distributed Lag (CS-DL) and Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) models, all developed by Chudik and Pesaran (2015). The Cross-Sectionally Augmented Distributed Lag (CS-DL) model is an extension of the traditional Distributed Lag model that captures cross-sectional averages of the dependent and independent variables to address cross-sectional dependence due to unobserved common factors (Chudik & Pesaran, 2015; Chudik, et al. 2016). The model is robust to weak cross-sectional dependence and it avoids biases from omitted common factors. Equation (4) specifies the CS-DL framework:

$$Y_{it} = \alpha_i + \sum_{j=0}^{p}\beta_j X_{i,t-j} + \sum_{j=0}^{q}\gamma_j \bar{X}_{i,t-j} + \sum_{j=0}^{q}\emptyset_j \bar{Y}_{i,t-j} + \varepsilon_{it} \quad (4)$$

$\bar{X}_t = \frac{1}{N}\sum_{i=1}^{N} X_{it}$: Cross-sectional average of the regressors; $\bar{Y}_t = \frac{1}{N}\sum_{i=1}^{N} Y_{it}$: Cross-sectional average of the dependent variable. β_j is the unit-specific short-run coefficients; γ_j, ϕ_j are the coefficients capturing cross-sectional dependence.

The CS-ARDL model builds on the CS-DL model by integrating lagged dependent variables that allows for the modeling of dynamic relationships and adjustment processes. It is preferred when there is heterogeneous dynamics across units, and particularly useful in macroeconomic panels where cross-sectional dependence arises from global shocks (Chudik, et al. 2016).

$$Y_{it} = \alpha_i + \sum_{j=0}^{p}\rho_{ij} Y_{i,t-j} + \sum_{j=0}^{q}\beta_{ij} X_{i,t-j} + \sum_{j=0}^{s}\gamma_j \bar{X}_{i,t-j} + \sum_{j=0}^{r}\emptyset_j \bar{Y}_{i,t-j} + \varepsilon_{it} \quad (5)$$

Where ρ_{ij} is the autoregressive coefficients for lagged Y_{it}; β_{ij} stands for Distributed lag c oefficients for X_{it} and γ_j,ϕ_j are the coefficients for cross-sectional averages.To ensure the robustness of the findings, we apply the Feasible Generalized Least Squares (FGLS) estimation technique, which efficiently handles issues of heteroskedasticity

and serial correlation in panel settings. FGLS also validates the main results obtained from the CS-DL and CS-ARDL frameworks.
We employed Fixed Effects (FE) regression with Driscoll-Kraay standard errors to examine the effects of human capital and carbon emissions on two key sustainability indicators: the renewable energy adoption rate and progress toward SDG-15 (life on land). This method was applied separately for the pre- and post-COVID-19 periods to capture potential structural shifts induced by the pandemic. Driscoll-Kraay standard errors corrects for heteroskedasticity, serial correlation, and cross-sectional dependence, which ensures of the robustness results even in the presence of unbalanced panels and correlated shocks across countries.

3. Results and discussions

Table 3 shows that the average renewable energy adoption rate across all the countries in the study is 63.63%. Thus, the countries source about two-thirds of their total energy from renewables. However, this wide range (0% to 98.3%) suggests significant disparities and extreme variations among the countries among the sub regions, Central Africa has the highest adoption, possibly because of hydropower dominance in Democratic Republic of Congo and Cameroon. This is followed by Eastern Africa, which could be due to the huge geothermal/wind investments in Kenya and Ethiopia.

Table 3. Summary statistics

		Green Energy Tech	SDG-15	Mean Years of Sch.	Carbon Emission	Real GDP (US$)	Regulatory Quality
Full	Obs.	897	851	897	897	897	897
	Mean	63.63	67.06	4.84	17.98	$32 Bil	-0.63
	Min	0	32.61	0	0.09	$645 Mil	-1.86
	Max	98.3	90.11	11.61	485.373	$535 Bil	0.90
Central	Obs.	184	161	184	184	184	184
	Mean	70.65	73.93	4.60	6.41	$21.2 Bil	-1.10
	Min	3.7	53.32	1.47	0.15	$1.62 Bil	-1.84
	Max	98.3	89.86	9.55	32.60	$90.5 Bil	0.22
East	Obs.	276	253	276	276	276	276
	Mean	69.80	60.65	5.28	4.14	$16.4 Bil	-0.55
	Min	0	32.61	1.16	0.09	$645 Mil	-1.55
	Max	96	82.32	11.37	21.53	$94.8 Bil	0.68
South	Obs.	115	115	115	115	115	115
	Mean	36.81	68.29	4.69	89.53	$67.1 Bil	0.03
	Min	0	41.57	0	0.36	$1.45 Bil	-0.76
	Max	69.30	90.11	11.61	485.37	$361 Bil	0.90
West	Obs.	322	322	322	322	322	322
	Mean	63.91	68.22	4.65	10.89	$39 Bil	-0.65
	Min	0	44.33	0.56	0.103	$705 Mil	-1.86
	Max	94.4	86.56	10.43	123.31	$535 Bil	0.27
	Ren. Energy Adopt.	1					
	Mean yrs. sch	0.086		1			
	Carbon	-0.282		-0.210	1		
	Real GDP	-0.004		-0.096	0.531	1	
	Reg. Qual.	-0.366		-0.058	0.277	0.191	1

West Africa has moderate adoption of about 64% indicating prevalence of mix of solar and hydropower. However, the lowest adoption rate of about 37% is observed among Southern African countries, which can be linked the sub-region's high reliance on coal. For instance, over 80% of electricity in South Africa is generated from coal-fired power plants (International Energy Agency (IEA), 2023). A similar was observed in terms of average progress toward achieving SDG-15 with Central Africa leading with (73.4%). Thus, the countries in the region are far away from attaining their target by SDGs' deadline, 2030.
Interestingly, the average carbon emission per capita for the full sample is as very low as about 18 metric tons due to high renewable energy adoption rate. Given the wide range (0.1 to 485.37), there is significant disparity in the emission across the countries. While Southern Africa is the worst emitter (89.53); Eastern Africa is cleanest (4.14), leveraging renewables.

Overall, there is low education levels as suggested full-sample average mean years of schooling (about 5 years). This means majority of the people in the region have primary education. Nonetheless, high variation in the schooling years as there are people with no formal education and people with almost 12 years of schooling. Average size of the economies in the selected sub-Saharan African countries is $32 billion but there is strong variation in the size, for the smallest economy is worth $645 million while the largest one is $535 billion during the period 2000-2022. Southern Africa has the largest economies that are worth $67.1 billion, trailed by Western African economies estimated at $39 billion.

There is weak regulatory quality as the average index (-0.63), which is close to the lowest score of -2.5. Southern Africa has relatively better regulatory quality than other sub regions. This is followed by Eastern Africa while Central Africa has the weakest regulatory quality.

Generally, the variables are weakly correlated as signified by low correlation coefficients. Only correlation between Carbon emissions and real GDP is positively strong, showing that industrialization leads to high carbon emission. Overall, multicollinearity is not a thing of concern for the models estimated.

Figures 1a and 1b illustrate the multidimensional relationship among education (SDG 4), renewable energy adoption (SDG 7), and carbon emissions (SDG 13).

Figure 1a demonstrates a **positive association between mean years of schooling and renewable energy adoption**, suggesting that human capital formation plays a vital role in facilitating clean-energy transitions. Countries with higher average schooling years, such as Kenya, Ghana, and Botswana, display greater renewable energy penetration. This pattern aligns with the premise that educated populations are more capable of understanding technical information, adopting innovations, and supporting policies that encourage sustainable energy use. Moreover, education fosters environmental awareness and behavioral change, thereby bridging SDG 4 (Quality Education) and SDG 7 (Affordable and Clean Energy).

Conversely, Figure 1b reveals a **negative relationship between carbon emissions and renewable energy adoption**, confirming the long-term incompatibility of fossil-fuel dependency with sustainable energy goals. Higher levels of CO_2 per capita often correspond to slower adoption of renewables, particularly in Southern Africa, where coal remains dominant. This figure underscores the **mitigation aspect of SDG 13 (Climate Action),** showing that efforts to decarbonize are both a cause and a consequence of increased renewable-energy uptake. The pattern also reveals a potential feedback loop: as emissions rise, ecological stress and policy pressure increase, which eventually stimulates investment in cleaner technologies. However, the lag between environmental deterioration and green-energy response highlights the need for proactive rather than reactive climate strategies.

Conclusively, Figures 1a and 1b jointly suggest that **human capital and environmental policy operate as complementary drivers of energy sustainability**. Education not only enhances technological readiness but also amplifies the public demand for environmental accountability, while emission control policies create economic incentives for renewable innovation. Together, they strengthen the integration of SDG 4, 7, and 13 within the broader sustainability framework.

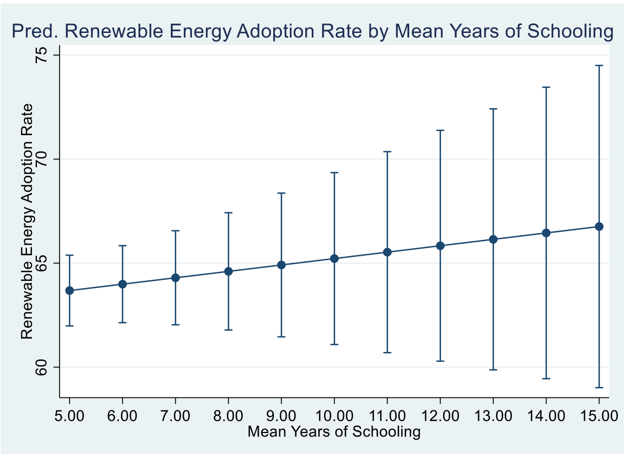

Figure 1a. Renewable energy vs. Education

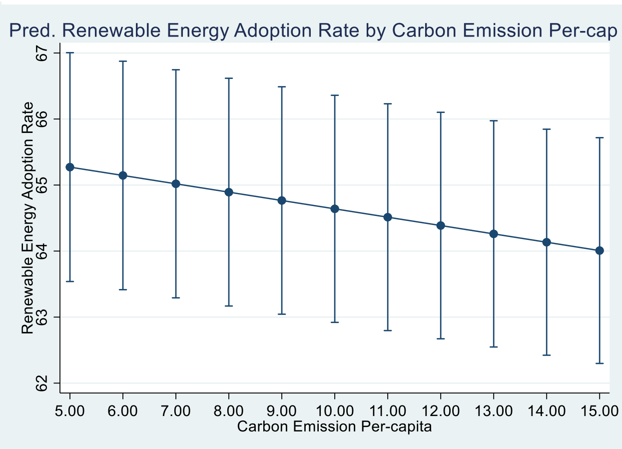

Figure 1b. Renewable energy vs. CO_2

Fig. 1a shows that renewable energy adoption rate generally increases with mean years of schooling. This signifies that educated populations tend prioritize sustainability by adopting green energy technology. Fig. 1b, however, reveals that higher carbon emissions are associated with lower renewable energy adoption.

Figures 2a and 2b deepen the analysis by linking human capital and environmental performance to **SDG 15 (Life on Land),** the preservation of terrestrial ecosystems.

Figure 2a shows a clear upward trend between mean years of schooling and SDG-15 performance, implying that education contributes indirectly to land sustainability. Educated communities are better equipped to engage in reforestation programs, biodiversity conservation, and responsible land management. This connection illustrates

how **SDG 4 (education)** supports **SDG 15 (life on land)** through improved environmental literacy, research capacity, and governance participation. It also reflects the diffusion of ecological values across generations – an outcome of formal and informal education that reinforces the social foundations of sustainability.
Figure 2b, however, reveals that higher carbon emissions correlate with lower SDG-15 progress, confirming the ecological cost of industrial and urban expansion. The deterioration of terrestrial ecosystems in countries with rising CO_2 output underscores the **trade-offs between economic growth, energy use, and land preservation**. This pattern highlights the interconnectedness of **SDG 13 (climate action)** and **SDG 15 (life on land):** as emissions intensify, climate-induced phenomena such as droughts, floods, and desertification directly threaten biodiversity and agricultural productivity.
Integrating these visual insights with the econometric findings demonstrates that **policy synergies across multiple SDGs are essential.** Investments in education and renewable energy have cascading benefits for climate mitigation and ecosystem protection, while unchecked fossil-fuel consumption undermines both environmental and developmental targets. Hence, the figures collectively portray a coherent SDG nexus – education enables green innovation (SDG 4 → 7), emission reduction strengthens climate resilience (SDG 13), and both outcomes safeguard terrestrial life (SDG 15).

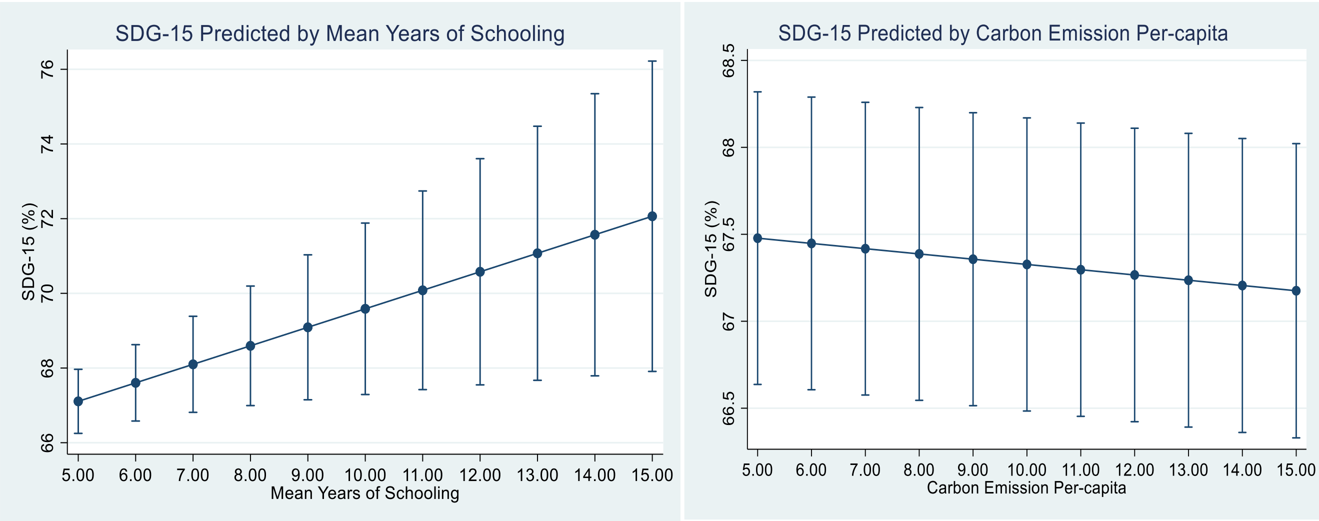

Figure 2a. SDG-15 vs. Education Figure 2b. SDG-15 vs. CO_2

Similarly, Fig. 2a reveals that progress toward achieving SDG-15 generally increases with mean years of schooling. This signifies that educated populations tend prioritize sustainability by adopting green energy technology. Fig. 2b, on the other hand, suggests that higher carbon emissions slow the progress toward achieving SDG-15.

Table 4. Second Generation Unit Root Test

Variables	**CIPS**		**CADF**	
	I(0)	**I(1)**	**I(0)**	**I(1)**
Green Energy Tech	-1.089	-6.627***	-3.237	1.723***
SDG-15	-1.272	-4.851***	-0.884	-6.529***
Mean Years of Sch.	6.745	304.446***	-4.027	89.676***
Carbon Emission	1.353	-8.309***	-5.038	27.629***
Real GDP (ln)	0.591	-7.098***	1.370	16.142***
Reg. Quality	-0.954	-12.150***	6.228***	--------------

***,**,* shows the significance level at 1%.5% and 10%,respectively

In Table 4, most variables are stationary at first difference, I(1), except regulatory quality, which is I(0) under Cross-sectionally Augmented Dickey Fuller test (CADF).
Pedroni test in Table 5 indicates that the Modified Phillips-Perron, Phillips-Perron, and ADF statistics are all statistically significant at the 1% level, with p-values of 0.000 and 0.001. This suggests strong evidence of cointegration among the variables. Similarly, Westerlund test shows that the variance ratio statistic is significant at the 5% level, which also supports the existence of cointegration. This confirms the robustness of the Pedroni results.

Table 5. Panel Cointegration Tests

	Pedroni Test		Westerlund Test	
	Statistics	Prob. Value	Statistics	Prob. Value
	Renewable Energy Rate as Dependent Variable			
Mod. Phillips-Perron	4.1285***	0.000		
Phillips-Perron	-3.866***	0.000		
ADF	-3.149***	0.001		
Variance ratio			-2.283**	0.011
	SDG-15 Dependent Variable			
Mod. Phillips-Perron	5.810***	0.000		
Phillips-Perron	-0.1110	0.456		
ADF	-2.339***	0.0097		
Variance ratio			1.894**	0.029

*** shows the significance level at 1%.

Given the presence of cross-section dependence in the variables and that the variables are mostly I(1), the study estimates cross-section augmented distributed lags (CS-DL) and cross-section augmented ARDL (CS-ARDL). In Table 6, the CS-DL results for full sample show that only change in carbon emission is significant (at 1%).

3.2. Aggregate analysis: results of renewable energy adoption rate models

Table 6. Cross-Section Augmented Distributed Lags (CS-DL) results for renewable energy

	Full Sample	Sub-regional Analysis			
Green Energy Tech		Central	East	South	West
Mean Years of Sch.	-4.448	0.649	-21.65	7.051***	-14.04
	(4.456)	(13.88)	(19.89)	(1.747)	(11.48)
Carbon Emission	1.857	4.652**	-0.304	1.661	2.413
	(1.249)	(1.779)	(1.883)	(1.322)	(2.046)
Real GDP (ln)	6.988	3.898	5.312	-19.08***	14.14*
	(4.599)	(15.86)	(10.01)	(7.010)	(8.507)
Reg. Quality	0.426	5.014	-3.279*	3.361	2.433
	(1.673)	(3.171)	(1.708)	(3.164)	(2.940)
Δ(Mean Years of Sch.)	6.525	-1.515	27.24**	-4.550**	11.79
	(4.559)	(16.82)	(12.31)	(2.067)	(11.29)
Δ(Carbon Emission)	-9.079**	-7.387*	-14.91	-5.523	-4.460**
	(4.116)	(4.237)	(13.39)	(3.907)	(1.985)
Δ(Real GDP)	-4.527	-3.871	-12.70	13.95	1.587
	(4.875)	(14.30)	(7.607)	(9.228)	(8.191)
Δ(Reg. Quality)	-2.236	7.792	0.579	0.508	-2.000
	(1.639)	(4.868)	(1.355)	(1.679)	(2.139)
R-squared (MG)					
Prob > F	0.78	0.99	0.000	0.080	0.020
CD test statistics	-2.35**	0.62	-0.76	0.09	-0.66
N x T	858	176	264	110	308

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

These results reinforce the multi-SDG nexus underpinning the analysis. The negative relationship between carbon emissions and renewable energy adoption underscores the tension between SDG 13 (climate action) and SDG 7 (clean energy). At the same time, the generally positive (though regionally mixed) effect of education on green energy adoption connects to SDG 4 (quality education) by highlighting the need for skilled human capital to enable sustainable energy transitions. The interlinkage with SDG 15 (life on land) arises through the environmental benefits of renewable energy deployment and reduced ecological pressure.

This means carbon emission has a short-term negative and significant effect on the rate of green energy adoption in the region. In Central Africa, the only significant variables are level and first difference in carbon emission.

This means carbon emission has both significant short and long-run effects. In the short run, the emission reduces green energy adoption by about 7.4% but it improves the adoption by about 4.7% in the long run. In Eastern sub region, the first-difference in education (mean years of schooling) shows a positive and significant effect on renewable energy adoption. However, the level of education has a negative coefficient (though not significant). The CS-DL results for Southern sub region indicate the first-difference of education is negatively associated with green energy adoption while the level of education has both positive and significant impact on the green energy adoption. Among the control variables, real GDP is negative and highly significant. Finally, the CS-DL results for Western

Africa reveals that first-difference of carbon emissions is significantly negative, reinforcing the idea that environmental degradation prompts green transitions.
Table 7 reports the CS-ARDL results and the results show that the lag of renewable energy adoption is highly significant across all regions except Southern Africa, indicating strong endogeneity. In the short term, carbon emissions exert a significantly negative impact in the full sample, Central Africa, Western, and Southern Africa (at 10%). This has corroborated the earlier finding that environmental degradation pushes countries to adopt renewables. Among the control variables, real GDP has negative and significant short-run effects in Southern Africa, suggesting that economic expansion in the short run is driven by fossil-fuel-intensive industries.

Table 7. Cross-Section Augmented ARDL (CS-ARDL) results for renewable energy

	Green Energy Tech	Pooled Sample	Sub-regional Analysis Central	East	South	West
Short-Run	Δ(Green Energy Tech) $_{t-1}$	-0.272***	-0.331***	-0.362***	-0.223	-0.352***
		(0.0439)	(0.0965)	(0.0810)	(0.276)	(0.0815)
	Carbon Emission	-1.426**	-2.661*	-8.875	-6.214*	-2.082**
		(0.726)	(1.351)	(7.002)	(3.491)	(0.853)
	Real GDP (ln)	-3.869	7.279	-16.49	-25.30***	16.49*
		(7.507)	(5.148)	(17.17)	(5.284)	(8.839)
	Reg. Quality	-0.0823	4.252	-3.841*	-2.620	-1.315
		(1.198)	(2.994)	(2.154)	(4.686)	(2.788)
	Mean Years of Sch.	2.937	-0.624	3.080	2.513	-0.0290
		(1.944)	(0.621)	(7.190)	(2.547)	(2.113)
Long Run	**ECT**	-1.272***	-1.331***	-1.362***	-1.223***	-1.352***
		(0.0439)	(0.0965)	(0.0810)	(0.276)	(0.0815)
	Reg. Quality	0.149	3.246	-2.594*	0.786	-2.387
		(1.165)	(2.120)	(1.525)	(3.578)	(3.537)
	Carbon Emission	-1.076**	-2.232*	-6.668	-4.385	-1.297**
		(0.539)	(1.170)	(5.273)	(3.092)	(0.645)
	Mean Years of Sch.	4.194	-0.441	2.004	1.767	-0.0304
		(3.475)	(0.438)	(4.616)	(2.277)	(1.714)
	Real GDP (ln)	-6.990	5.256	-11.00	-37.86	10.45**
		(9.129)	(3.690)	(12.77)	(22.77)	(4.971)
	N x T	819	168	252	105	294
	R-squared	0.563	0.483	0.308	0.421	0.479
	CD Test Statistics	-1.03	-1.80*	-0.47	-0.36	0.22

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

The error correction term (ECT) is negative and significant across all samples, confirming the presence of a stable long-run equilibrium relationship between green energy adoption and the explanatory variables. The speed of adjustment is high (ECTs range from -1.22 to -1.36), suggesting rapid convergence to equilibrium after a shock. Long-run carbon emissions remain negatively associated with renewable energy adoption in the pooled sample, Central, and West Africa. The coefficients are significant, signifying steady pressure to transition from dirty energy sources. Regulatory quality has mixed effects; insignificant in most cases but negative and significant in East Africa. This may reflect that tighter or poorly implemented regulations, rather than facilitating, may hinder renewable energy expansion in that region.

3.2.1. Results of progress toward SDG-15 models

The results in Table 8, based on Cross-Section Augmented Distributed Lag (CS-DL) models, explore the drivers of SDG-15 progress (life on land) across Sub-Saharan Africa. For the full sample, mean years of schooling has a positive and statistically significant effect (at the 10%). This implies that higher educational attainment improves progress toward SDG-15 outcomes – potentially through increased environmental awareness, better resource management practices, and stronger civil engagement in land preservation.
However, the results in Table 8 show that the short-run effect of changes in mean years of schooling (ΔMean Years of Sch.) is negative and statistically significant at the 5%. This means that while long-term improvements in education enhance progress toward achieving SDG-15, short-term expansions in schooling tend to slow down the progress, possibly due to urban expansion pressures, which temporarily undermine environmental sustainability goals. Carbon Emissions show a positive but insignificant effect, suggesting that emission levels do not significantly influence SDG-15 progress in the full sample. Although it is only significant at 10%, regulatory quality slows down the SDG-15 progress, perhaps due to ineffective or poorly enforced regulations that hinder sustainable land use.

Table 8. Cross-Section Augmented Distributed Lags (CS-DL) results for SDG-15 progress

SDG15	Full Sample	Sub-regional Analysis			
		Central	East	South	West
Mean Years of Sch.	7.078*	3.098	4.373	-3.796	19.34
	(3.956)	(5.494)	(3.071)	(4.099)	(22.93)
Carbon Emission	5.867	-0.576	5.477	7.841	-0.244
	(8.565)	(0.556)	(5.987)	(9.212)	(2.484)
Real GDP (ln)	-13.80	0.258	-22.67	10.15	-21.60**
	(13.35)	(5.416)	(26.71)	(7.058)	(10.43)
Reg. Quality	-2.757*	-0.0182	-1.778	-1.296	-0.507
	(1.462)	(2.297)	(1.255)	(0.987)	(1.060)
Δ(Mean Years of Sch.)	-8.008**	-5.048	-4.430*	3.261	-22.41
	(3.770)	(5.300)	(2.438)	(3.634)	(22.44)
Δ(Carbon Emission)	-0.145	0.592**	-1.925	-5.121	0.953
	(1.328)	(0.293)	(3.706)	(5.240)	(2.292)
Δ(Real GDP)	-5.068	-3.362	11.10	-13.30**	0.190
	(5.022)	(7.819)	(15.69)	(5.574)	(9.419)
Δ(Reg. Quality)	3.156	-0.276	0.112	0.709	3.460
	(2.277)	(0.341)	(0.965)	(0.841)	(2.711)
N x T	814	154	242	110	308
R-squared	0.488	0.089	0.475	0.220	0.485
CD Test Statistics	5.33***	-2.06**	-0.77	0.01	2.28**

Standard errors in parentheses

The short-term change in emissions has a positive and significant effect on SDG-15 progress in Central Africa, possibly land expansion for agricultural purposes. In East Africa, change in mean years of schooling is negative and significant at the 10% level, reflecting the short-term disruption observed in the full sample. This suggests that in East Africa, increases in educational access may initially correlate with environmental pressures, possibly due to land conversion for school infrastructure or demographic shifts.

In Southern Africa, the only significant variable is change Real GDP, which has a negative effect. This implies that short-term economic growth in this sub-region conflicts with sustainability, likely due to mining, infrastructure expansion, or industrial development. For West Africa, long-run real GDP is significantly negative at the 5%, supporting the Southern African finding that economic expansion, if unregulated, can harm SDG-15 progress. Despite addressing cross-section dependence, the problem persists in full sample and West African results.

Table 9. Cross-Section Augmented ARDL (CS-ARDL) results for SDG-15 progress

SDG15	Pooled Sample	Sub-regional Analysis			
		Central	East	South	West
Δ(SDG-15) t-1	-0.0325	-0.235***	0.0219	-0.317	-0.223***
	(0.0800)	(0.0809)	(0.161)	(0.206)	(0.0662)
Mean Years of Sch.	-1.287**	-1.426	-2.332	-0.0262	-0.528
	(0.603)	(1.221)	(1.505)	(0.186)	(0.814)
Carbon Emission	3.188	0.193	4.800	1.019	-0.636
	(4.183)	(0.537)	(6.374)	(1.582)	(4.975)
Real GDP (ln)	-8.782	-1.497	-17.03	-2.109	6.278
	(8.371)	(3.905)	(16.57)	(3.888)	(10.59)
Reg. Quality	0.854	0.145	1.188**	-1.603**	3.604
	(0.840)	(2.033)	(0.467)	(0.700)	(3.140)
ECT	-1.033***	-1.235***	-0.978***	-1.317***	-1.223***
	(0.0800)	(0.0809)	(0.161)	(0.206)	(0.0662)
Reg. Quality	1.337	0.441	3.342	-1.593*	3.324
	(0.943)	(1.891)	(2.140)	(0.833)	(2.643)
Carbon Emission	3.000	0.173	-361.1	1.320	0.0940
	(4.613)	(0.512)	(359.6)	(1.860)	(3.506)
Mean Years of Sch.	-1.922	-1.058	67.88	-0.0107	-0.587
	(1.325)	(0.993)	(68.22)	(0.174)	(0.743)
Real GDP (ln)	-12.16	-0.523	874.2	-0.769	3.254
	(8.965)	(3.649)	(879.6)	(4.220)	(8.790)
N x T	777	147	231	105	294
R-squared	0.660	0.079	0.382	0.576	0.596
Number of groups	3.64***	-2.38**	-1.19	-1.85*	2.81***

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

The Cross-Section Augmented Autoregressive Distributed Lag (CS-ARDL) results in Table 9 analyze the short- and long-term effects of carbon emissions and mean years of schooling on SDG-15 progress (life on land) across Sub-Saharan Africa and its sub-regions. In the pooled sample, mean years of schooling is negative and significant at the 5% level, meaning that higher education levels, in the long run, lowers SDG-15 performance. While none of the variables is significant in Central Africa, regulatory quality positively and significantly influences SDG-15 progress in East Africa.

On the contrary, regulatory quality is negative and significant in Southern Africa, perhaps due to ineffective implementation of land reform or mining regulations. The error correction terms (ECTs) are consistently significant and negative across all models, reaffirming that the system adjusts toward long-run equilibrium after the short-term disturbances. Relying on the CS-ARDL findings, the results show that education consistently undermines SDG-15 progress, suggesting structural development-environment tradeoffs in SSA. The results provide an evidence revealing East Africa's unique positive regulatory quality effect versus Southern Africa's negative governance impact.

3.3. Disaggregated analysis: pre- and COVID-19 pandemic analyses: renewable energy adoption Rate & SDG-15

This section presents the effects of education and carbon emission on renewable energy adoption rate and SDG-15 progress.

Table 10. Fixed-effect Regression with Driscoll-Kraay Standard Errors results

	Renewable Energy Rate		SDG-15	
VARIABLES	**Pre-COVID**	**COVID**	**Pre-COVID**	**COVID**
Mean Years of Sch.	1.204***	-0.719**	2.844***	-0.054**
	(0.161)	(0.097)	(0.206)	(0.011)
Carbon Emission	-0.062***	-1.485	-0.028***	-0.123
	(0.009)	(0.527)	(0.00765)	(0.0435)
Real GDP (ln)	-12.11***	-114.3*	0.972	9.591**
	(0.472)	(32.00)	(0.796)	(1.961)
Reg. Quality	-0.365	26.35	0.781	-1.799
	(0.579)	(9.487)	(1.155)	(1.409)
Constant	342.1***	2,790*	31.88	-155.1*
	(10.73)	(752.4)	(18.84)	(45.51)
Within R^2	0.471	0.152	0.214	0.076
Prob > F	203.04***	10.02*	69.10***	13.00*
Observations	740	111	740	111
Number of groups	37	37	37	37

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

Table 10 presents the Fixed-effect Regression with Driscoll-Kraay standard errors results. Prior to the COVID-19 pandemic, mean years of schooling had a significant and positive effect on both renewable energy rate and SDG-15 progress, both significant at the 1% level. This reveals that higher educational attainment promote sustainability, possibly by increasing public awareness, facilitating innovation, and influencing policy preference toward renewable energy and biodiversity preservation. Conversely, COVID, the effect reversed.

Table 10 indicates that Carbon emissions had a negative and significant effect on both dependent variables in the pre-COVID period. Interestingly, COVID, carbon emissions were not statistically significant, though still negative. In the table, real GDP a negatively and significantly affects renewable energy pre-COVID. However, COVID, GDP's effect became more extreme and volatile, reflecting uncertainty or structural fragility in energy sector. For SDG-15, GDP was insignificant pre-COVID but became positively significant COVID, suggesting that economic recovery efforts may have included biodiversity-enhancing investments.

4. Interpretation

Evident across CS-DL, CS-ARDL, and FGLS, carbon emissions remain negative and significant, at least in the short run determining the adoption of green energy technology in the full sample, Central, and West Africa. This finding resonates with those of Olanrele and Fuinhas (2021) and Özbay and Duyar (2022). The finding is farfetched majority countries in SSA and West Africa including Nigeria, and Angola depend profoundly on fossil fuel exports (oil, gas, coal) for revenue. This creates a *carbon lock-in* effect, where embedded fossil fuel infrastructure and vested interests resist renewable transitions. Again, fuel subsidies discourage the adoption green energy technology (Adewuyi & Awodumi, 2017).

Conversely, mean years of schooling is mostly positive but insignificant in impacting green energy adoption among sub-Saharan African countries. The CS-DL results reveal that the mean years of schooling has a positive and significant effect among Central African countries in the short term. While it is positively significant in the long term for Southern Africa, it has a negative and significant effect in the short term. In Central Africa, a short-term positive effect of education on green energy adoption may reflect the need for immediate deployment of technical skills in nascent renewable sectors.

Educated workers tend to quickly adapt to roles in renewable projects, thereby speed up the implementation. In another sense, educated populations tend to understand the benefits of clean energy, assimilate technical information, and support policy reforms favoring green transitions. This is consistent with Özbay and Duyar (2022). Southern Africa's economies (such as South Africa, Botswana) are heavily reliant on fossil fuel industries. In the short term, educated populations may be attracted toward higher-paying fossil fuel jobs or emigrate (*brain drain*), which may delay the green energy transitions. South Africa's coal sector employs about 90,000 skilled workers (IEA, 2023), creating a *lock-in* effect where education perpetuates fossil fuel dependence. Over time, education may promote environmental awareness, innovation, and policy advocacy. A more educated populace can demand cleaner energy and support regulatory reforms.

Findings from SDG-15 analysis point to an evidence that mean years of schooling shows a consistent negative and statistically significant impact on SDG-15 in the pooled sample. This finding is counterintuitive and might reflect that higher education levels in SSA require conversion of land schools so as to accommodate more students and then increase their years of learning. The finding might also reveal increased urbanization, economic development, and infrastructure expansion. Ultimately, these pressures on the land result in the loss of natural habitats and biodiversity.

Furthermore, regulatory quality appear to be significant but regionally divergent; positive in East Africa, where land tenure reforms and decentralized governance might be yielding results, and negative in Southern Africa, possibly due to weak enforcement. Also, the regulatory quality is negative, perhaps, the regulatory framework favors extractive industries, thereby undermine land conservation efforts. The pre-COVID-19 results show that education had a strong and positive impact on both renewable energy adoption and SDG-15 progress, consistent with earlier findings in the studies (Adewuyi & Awodumi, 2017; Özbay & Duyar, 2022). However, COVID, this effect turned negative and remained significant. This could be due to economic disruptions, reallocation of public budgets away from education and environment, or lagged effects of pandemic-induced migration and land-use changes. The carbon emissions variable, which was significantly negative in the pre-COVID period, lost significance COVID, suggesting a possible decoupling effect or masking of emissions trends by temporary lockdowns and reduced industrial activity.

5. Conclusion

This study aligns with four core Sustainable Development Goals: **SDG 4 (Quality Education)**, **SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action)**, and **SDG 15 (Life on Land)**. Using data from 39 Sub-Saharan African countries (2000–2022), the analysis establishes that human capital, energy transition, and carbon management are mutually reinforcing pillars of sustainable development. The analysis carried out across 39 Sub-Saharan African countries between 2000 and 2022 reveals significant relationships between carbon emissions, human capital, and the adoption of green energy technologies – elements that are at the heart of global sustainable development efforts.

Starting with SDG 7, which aims to ensure access to affordable, reliable, sustainable, and modern energy for all, the study reveals that the average rate of renewable energy adoption across SSA is relatively high at 63.63%. However, this regional average mask deep sub-regional disparities. Central and Eastern Africa exhibit higher adoption rates due to greater hydropower and geothermal potential, whereas Southern Africa – heavily reliant on coal—lags behind. These findings align with SDG Target 7.1, which emphasizes universal access to affordable, reliable, and modern energy services. The evidence suggests that although some SSA regions have made progress toward this goal, others still face significant challenges, particularly in transitioning from fossil fuels to sustainable alternatives.

Additionally, the study supports SDG Target 7.2, which calls for a substantial increase in the share of renewable energy in the global energy mix. The empirical results show that carbon emissions are negatively associated with renewable energy adoption, particularly in countries with high fossil fuel dependence. This implies that reducing reliance on fossil fuels is essential not only for meeting climate targets but also for increasing renewable energy uptake. Regarding **SDG 13,** beyond the CO_2 metric, climate action encompasses adaptive capacity, institutional readiness, and resilience financing – dimensions that SSA nations must strengthen to complement emission-reduction efforts.

Furthermore, the call to phase out fossil fuel subsidies and reallocate resources toward clean energy initiatives reinforces SDG Target 7.A, which encourages enhanced international cooperation to facilitate access to clean energy research and technology. The study's emphasis on regional collaboration – particularly for countries with shared energy infrastructures – aligns well with SDG Target 7.B, which promotes infrastructure development and technological upgrades for sustainable energy.

Turning to SDG 13, which focuses on urgent action to combat climate change and its impacts, the study provides a robust argument that environmental degradation is a powerful driver of green energy transitions in SSA. The use of carbon emissions as a key independent variable reveals that higher emissions significantly reduce green energy adoption, both in the short and long term. However, in some cases, the realization of these environmental consequences has triggered policy shifts toward renewables. This feedback loop supports SDG Target 13.2, which calls for the integration of climate change measures into national policies, strategies, and planning. By providing empirical evidence that environmental degradation prompts policy change, the study highlights the role of emissions data as both a diagnostic and planning tool for governments in SSA.

Furthermore, the paper discusses the importance of building regulatory and institutional capacity to support the renewable energy transition. Weak or poorly implemented regulations were shown to hinder clean energy development in some regions, suggesting a gap in governance. This finding resonates with SDG Target 13.B, which emphasizes the need to build institutional and human capacity for effective climate planning, particularly in developing countries. The recommendation to strengthen regional collaboration and create enabling policy environments provides a practical pathway for achieving this goal. Moreover, the study's methodological robustness, which uses second-generation panel estimations to capture inter-country linkages, underscores the importance of regional interconnectedness in addressing global climate challenges.

Equally significant is the alignment of the study with SDG 4, which promotes inclusive and equitable quality education and lifelong learning opportunities for all. The study uses mean years of schooling as a proxy for human capital and finds that educational attainment, though not uniformly significant across all regions, positively influences the adoption of green energy technologies in key contexts. In Central Africa, for example, an increase in education levels was associated with short-term gains in renewable energy adoption, while in Southern Africa, the impact was more prominent in the long run. These findings highlight the importance of education in equipping individuals with the technical and cognitive skills needed to engage with, manage, and promote clean energy technologies. This directly supports SDG Target 4.3, which aims to ensure equal access for all women and men to affordable and quality technical, vocational, and tertiary education.

Moreover, the study's recommendation to reform education systems to prioritize renewable energy training is closely aligned with SDG Target 4.4, which focuses on substantially increasing the number of youth and adults with relevant skills for employment, decent jobs, and entrepreneurship. A skilled workforce is essential for the effective deployment and maintenance of green technologies. In many SSA countries, the lack of trained personnel has been a barrier to the expansion of solar, wind, and bioenergy projects. This creates a bottleneck where even with financial resources and political will, technical limitations prevent rapid progress. By addressing this human capital gap, countries can simultaneously advance educational and environmental goals.

The indirect effects of education on environmental sustainability also support SDG Target 4.7, which calls for learners to acquire the knowledge and skills needed to promote sustainable development. Educated individuals are more likely to adopt pro-environmental behaviors, understand the implications of climate change, and support policies that promote clean energy. Over time, a well-informed public can become a powerful force for policy advocacy, innovation, and community-led energy initiatives.

Overall, this study serves as a compelling evidence base for aligning energy policy in Sub-Saharan Africa with the broader objectives of the 2030 Agenda for Sustainable Development. By illustrating how carbon emissions, education, and regulatory quality interact to influence green energy adoption, the paper underscores the interconnected nature of the SDGs. It shows that progress on one goal – such as improving education – can accelerate achievement in others, like expanding clean energy access and reducing carbon emissions. The findings call for integrated policy approaches that recognize these interlinkages and prioritize investments that yield multiple SDG co-benefits. Through context-specific strategies and enhanced regional cooperation, Sub-Saharan African countries can accelerate their transition to a low-carbon future while achieving inclusive and sustainable development.

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