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Structural Transformation, Energy Intensity, and GHG Emissions in East Africa: Implications for Green Development

Ademati, Akeem Oladele[a,*], **Bonabana-Wabbi, Jackline**[a,1], **Nalunga, Asha**[a,1]

[a]*Department of Agribusiness and Natural Resource Economics, Makerere University, Kampala, Uganda*

Abstract

This paper dissected the intricate drivers of per-capita greenhouse gas emissions across East Africa, with a laser focus on the dynamics of sectoral shifts in synergy with the shockwaves of energy consumption for a time period of 1993 to 2022. The study engaged a balanced panel of five East African countries which are Burundi, Kenya, Rwanda, Tanzania, Uganda. The balanced panel was designed by combining EDGAR's IPCC published greenhouse gases data with salient macro-economic variables and indicators harvested from World Bank's WDI data. The research revealed how fixed and random effect models coherently synergize with common correlated effects (CCE) estimators and cross-sectional augmented ARDL (CS-ARDL) to x-ray the intricate nexus of cross-sectoral feedbacks while informing of the short-run and long-run impacts.

The outcome of this research clearly revealed that per-capita GDP is the primary driver of emissions in the region, with elasticities of 0.7–0.8. Furthermore, it was revealed that per-capita energy usage has a strongly positive effect (elasticity ≈ 0.42). In the same vein, trade openness mitigates the intensity of emissions when heterogeneity is controlled for. Moreover, sectoral composition and urbanization indirectly matter by producing effects on growth and energy demand.

The research conducted cross-sectional dependence tests which affirmed strong regional spillovers, thereby emphasizing the need for the East African block to adopt sustainable energy and climate strategies.

The findings of this research safely concluded that without major investments in renewable energy, energy efficiency, and climate-friendly industrial transition, the East African region is bound to be entrapped into an emissions-intensive growth path. Meanwhile, the early adoption of climate-friendly technologies and regional sustainability efforts offers viable

*Corresponding author.

Email addresses: ademati.akeemoladele@students.mak.ac.ug (Ademati, Akeem Oladele), Jackline.bonabana@mak.ac.ug (Bonabana-Wabbi, Jackline), Asha.Nalunga@mak.ac.ug (Nalunga, Asha)

prospects to decouple growth from emissions at an earlier stage of development with hope for a resounding success that is uncommon.

Keywords: Sectoral Shifts, Energy use, Per-capita GHG emissions, East Africa, Renewable energy, Panel econometrics
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1 Introduction

The dynamic process of economic transformation and expansion is historically energy-intensive, whereas the burning of energy is the principal driver of greenhouse gas emissions across the globe. With the boom of global population triggering economic expansion, energy demand to meet economic needs is inevitable, thereby ramping up GHG emissions.[1, 2, 3, 4] Moreover, as economies expand, there are fast, dynamic, evolving shifts from one economic sector to another motivated by several factors such as resource availability, technical know-how, labour availability, capital availability, profit motives, etc., thereby leading to gradual transitions between economic activities/sectors [1, 2, 3, 4].

It is difficult to separate economic expansion in developing countries from exponential growth in energy demand, as the process smoothens into rapid population growth and urban expansion. Sectoral shifts such as transition from agricultural sector to industrial sector further aggravate energy demand and ultimately growing emissions output, especially in an economy heavily dependent on fossil fuels for energy needs. Therefore, the policy of balancing economic advancement with a decline in greenhouse gas emissions raises many debates. Empirical evidence, however, suggests that aligning economic growth with declining greenhouse gas emissions is attainable. Notable countries that successfully decoupled growth from emissions, such as Germany, UK, and France, achieved the feat by reducing the intensity of emissions and decarbonizing their supply chains. The main drivers of this decoupling success include investments in clean energy, environmentally friendly technologies, and green innovations, thereby increasing productivity while simultaneously reducing emission outputs.

This is largely controlled by carefully designed systems such as emissions trading systems, carbon markets, green finance, and carbon credits. These systems are essential for the attainment of progressively green, inclusive, and sustainable growth that positions future generations well for development and prosperity while protecting the environment [5, 6]. Global efforts such as the Paris Climate Accord draw attention to this crisis by motivating the entire globe to decouple economic growth from carbon emissions while attaining sustained energy sufficiency and poverty reduction at the same time.

In low- and middle-income economies, however, it can be observed that economic growth ramps up significant greenhouse gas emissions, since energy usage is largely fossil fuel dependent for industrial expansion and other machine usages. Decoupling emissions from growth has therefore become a systemic challenge in developing economies, with few embracing clean technologies, green innovations, and renewable energy while at the same time accelerating deforestation, biodiversity depletion, and ecosystem decimation [7, 8, 9]. Africa's case is also unique, with abundance of natural resources, an economy that is fast diversifying into several sectors, nonetheless the tempo of which has been hampered by limited energy infrastructure [10, 11, 12].

On global average, the overall contribution of the African continent to global per-capita emissions is the least on continental assessment. Nonetheless, the continent is the most vulnerable to the adverse impact of a fast-changing climate [13, 14, 15]. Therefore, the unique situation of the African continent being a low-emitting continent but highly vulnerable to the adverse impact of climate change underscores the imperative to achieve environmental sustainability goals. Research reveals several policies that can make African economies well positioned on a trajectory to attain sustainable growth, including but not limited to adoption of sustainable land management practices, carbon finance, use of renewable energy sources, environmentally friendly regulations enforcement, circular economy approaches, etc. These help translate into low carbon output and help attain international climate commitments [16, 17].

In the same vein, the East African block is synonymous with a fast booming population growth and urban expansion, thereby posing significant and daunting challenges for sustainable development, infrastructural balance, and environmental management goals.

This problem is further complicated with the population projected outlook forecasted to keep rising at a sustained pace, with some estimations projecting to reach two and a half billion population by the year 2050. This growth rate is made possible due to a high birth rate coupled with decreasing mortality rate. If this high population growth trajectory is sustained, it will put a strain on available resources and pressure the environment at large.

Thereby leading to stiff competition, social unrest, high unemployment, and food insecurity concerns among others. Efforts to address these challenges therefore need to balance population growth, urban expansion management, resource utilization planning, etc.

To address this myriad of problems, country-specific integrated strategies are therefore needed to provide feasible and lasting solutions, ensuring robust infrastructure development, sustainable growth, and environmental management to attain a conducive and prosperous economy for the East African community [18, 19, 20, 21, 22, 23].

Sectoral shifts are apparently coming to limelight in the East African block with the fast eroding dominance of the agricultural sector, the expansion of the service sector, and the slow but progressive rise of industrialization [24].

These economic transformations can be attributed to the growing energy demands and ultimately linked to emissions patterns. Moreso, declining agricultural dominance, expanding services, and slowly advancing industrialization are empirically associated with a ramped-up fossil fuel energy demand and invariably an off-chart emissions pattern. As East African economies transition from the agricultural sector to industrial or services sector, overall greenhouse gases emissions incline at an unfettered pace if not checked by efficiency in energy usage or adoption of clean and environmentally friendly energy sources [25, 26].

Even though energy access has been on the rise in the East African block in recent times, it is worthy of note that the region still heavily consumes fossil fuel and biomass-based fuels. Nonetheless, the region's energy consumption remains comparably low when compared to average global emitters. East Africa's energy consumption is predominantly traditional biomass, as it is not uncommon for most rural households to use charcoal and firewood for cooking and heating, thereby constituting several environmental and health challenges.

The region increasingly adopts fossil fuels for electricity generation, but biomass is the primary source of energy for most countries in the region. Nonetheless, electricity access is limited in the rural areas, thereby making the region one of the least electrified regions of the world.

The energy intensity in the region is low because the scale of industrialization is low and the use of energy is largely inefficient, especially in residential areas. Moreso, inefficient technologies, technical, financial, and policy barriers inhibit efforts to modernize the energy sector [27, 28, 29]. The East African region is at a formative but very crucial stage where it is germane to ensure that economic growth does not spiral emission trajectories out of control and ensure sustainable structural transformation.

There are several studies that hover around the growth-emission nexus, with most samples in the globe focusing on Asia and Latin America. With the uniqueness of Africa's rapid population growth rate left in question, moreso few studies break down emissions into sectoral value-added shares even though empirical findings largely suggest that there are differences in the contributions of the Agriculture, Industrial, and Services sectors. Likewise, even fewer studies bring in the energy access and blended energy mix into econometric models, not leaving out the fact that most standard panels rarely dissect cross-sectional dependence even though evidence suggests there are shocks and spillovers in African economies. These therefore leave a gap and urgent need to provide systematic evidence on how sectoral shifts and energy use affect emission trajectories in the East Africa Community.

This leads the research to ask three core questions:

1. How do sectoral shares of agriculture, industry, and services tell on per-capita GHG emissions while controlling for income, trade, and demographic factors in the East African Community?
2. Do energy use and energy access indicators increase explanatory power for models of emissions variation?
3. Does the results robustness increase when accounting for cross-country spillovers and cross-sectional dependence?

This paper therefore seeks to reveal from empirical theories how the Environmental Kuznet Curve shows a non-linear link between income growth and environmental degradation [30, 31, 32, 33]. Furthermore, this paper contributes to structural change research on industrialization versus services-led growth [34, 35, 36]. Moreso, it digs into energy-economics work on energy intensity and the composition of energy use as drivers of emissions [37, 38, 39]. In the same vein, the research seeks to strike a balance between trade–environment debates concerning openness, pollution havens, and technology transfer [40, 41, 42]. East Africa is a perfect study area due to its distinct development stage and unique sectoral shifts.

2 Data and Methodology

This research engaged a designed panel of five countries in the East African community of the eight countries in the block, providing a balanced country-year panel for the selected five East African economies (Burundi, Kenya, Rwanda, Tanzania, and Uganda) covering a time period of thirty years from 1993–2022. After verifying the panel data's iso3–year structure, the final dataset contains 150 observations (5 countries $\times$ 30 years) with no duplicates.

2.1 Greenhouse Gas Emissions

The data for greenhouse gas (GHG) emissions are sourced from the European Union's EDGAR database, which reports detailed flows in line with IPCC sectoral classification (e.g., energy industries, manufacturing, transport, agriculture, waste, and industrial processes). Since the emissions sectoral classification from EDGAR is different from the economic sectoral classification intended for use, therefore to align both the study reclassified EDGAR subsectors into three broad economic aggregates following our own self-constructed aggregation scheme (see table below):

- **Agricultural emissions:** Enteric fermentation, manure management, rice cultivation, direct/indirect N_2O from soils, and related sources.
- **Industrial emissions:** Main activity electricity and heat, manufacturing industries, cement, lime, glass, metal production, petroleum refining, oil and gas, and process uses of carbonates.
- **Services/household emissions:** Residential and commercial energy use, road and other transport, waste disposal and treatment, and non-energy product uses.

The study retained country-level totals for cross-checking. Furthermore, the study normalized all emissions by population (obtained from WDI) to derive the greenhouse gas emissions per capita (GHGpc). The dependent variable for the econometric analysis is the natural logarithm of per-capita GHG emissions ($\ln \text{GHGpc}$).

Table 1: Matching EDGAR emission categories to economic-sector aggregates

Aggregate Sector	EDGAR Categories Included
Agriculture	Enteric fermentation; Manure management; Rice cultivation; Direct and indirect N_2O from agricultural soils; Field burning of agricultural residues; Other agricultural sources.
Industry	Industrial emissions: Main activity electricity and heat, manufacturing industries and construction, cement production, lime, glass, and other mineral products, iron and steel production, non-ferrous metals, petroleum refining, oil and gas extraction and processing, process uses of carbonates, other industrial processes.
Services / Households	Residential and commercial energy use, road and other transport, waste disposal and treatment, and non-energy use.

2.2 Macroeconomic and Sectoral Variables

The macroeconomic indicators that were used for the research were taken from the World Bank's World Development Indicators (WDI). The key variables adopted include GDP per capita (constant US$, which was logged as $\ln \text{GDPpc}$), trade openness which was derived as (exports + imports as % of GDP), urban population (as % of total), population density (people per km^2), and population growth (annual %).

To estimate sectoral shifts, this is proxied by the value-added shares of agriculture (AgrShare), industry (IndShare), and services (SrvShare) in GDP. These three components sum to 100%, which mitigates omitted-variable bias associated with partial inclusion.

2.3 Energy Block (Robustness Variables)

The study also conducted robustness checks, by extending the specification with an energy block that captures both intensity and composition: per-capita energy use (kg of oil equivalent, logged as $\ln \text{EnergyPC}$), the share of fossil fuels in total primary energy (FossilShare), the share of renewables (RenewShare), and access to electricity (% of population, ElecAccess).

2.4 Variable Construction and Descriptives

The study log-transformed GHGpc, GDPpc, and EnergyPC to reduce skewness and allow elasticities to be interpreted directly. Sectoral shares, trade, urbanization, and demographic indicators remain in levels (percentages).

Summary statistics confirm expected patterns: GHGpc is lowest in Burundi and Rwanda, highest in Kenya; GDPpc rises steadily but remains low compared to global averages. Sectoral shares reveal a gradual decline in agriculture and expansion of services, while industrial shares increase only slowly. EnergyPC shows wide cross-country variation, with Tanzania and Kenya recording faster increases. Outlier years linked to the 2008 financial crisis and the 2020 pandemic are flagged for robustness.

2.5 Econometric Specification

The baseline empirical specification relates per-capita emissions to income, trade openness, and energy use:

$$\ln(\text{GHGpc}_{it}) = \alpha_i + \beta_1 \ln(\text{GDPpc}_{it}) + \beta_2 \text{Trade}_{it} + \beta_3 \text{EnergyPC}_{it} + \varepsilon_{it} \quad (1)$$

where i indexes countries and t indexes time. α_i captures unobserved time-invariant country-specific effects.

A Hausman test strongly rejects the random-effects estimator, indicating correlation between regressors and country-specific effects. Accordingly, fixed-effects estimation is adopted.

2.6 Diagnostic Tests and Robust Inference

To ensure safe conclusions and reliable deductions, the study harnessed diagnostic testing which reveals the presence of groupwise heteroskedasticity and cross-sectional dependence. Furthermore, to ensure that the inferences are consistent, the preferred specification employs Driscoll–Kraay standard errors, which are robust to heteroskedasticity, serial correlation, and general forms of cross-sectional dependence.

The final model therefore provides within-country estimates of the relationship between economic growth, trade openness, energy use, and per-capita emissions, while accounting for structural heterogeneity and regional spillovers.

3 Results

3.1 Descriptive Statistics

Table 2 clearly shows the Descriptive Statistics of Core Variables that were engaged in the study (1993-2022, 5 countries). The result shows that Per-capita GHG emissions remain very low by average global standards in the study area, while the agricultural sector dominates GDP shares, energy use per capita is modest, and urbanization is accelerating.

Table 2: Descriptive statistics of core variables engaged in the study (1993–2022, 5 countries)

Variable	Mean	Std. Dev.	Min	Max
ln(GHGpc)	-0.32	0.68	-1.57	1.23
ln(GDPpc)	6.49	0.39	5.82	7.34
AgrShare (%)	36.2	7.1	22.4	48.9
IndShare (%)	20.5	4.8	11.2	29.6
SrvShare (%)	43.3	8.2	32.1	58.2
Trade (% GDP)	42.7	13.2	20.6	69.8
Urban (%)	24.3	8.7	7.4	41.6
PopDensity (per km^2)	149	73.5	62.0	298
EnergyPC (kgOE per capita)	423	142	168	812

Figure 1 shows the trends in per-capita GHG emissions (lnGHGpc) in the study area, 1993-2022. This illustration reveals that emissions per capita is averagely low in the block, however it can be observed thay there is a gradual increment, with the illustration showing that Kenya and Tanzania's emission is consistently above that ofnBurundi and Rwanda; Moreso Uganda shows intermediate output when viewed compared to others, this reflects varied structural and energy transitions across the study area.

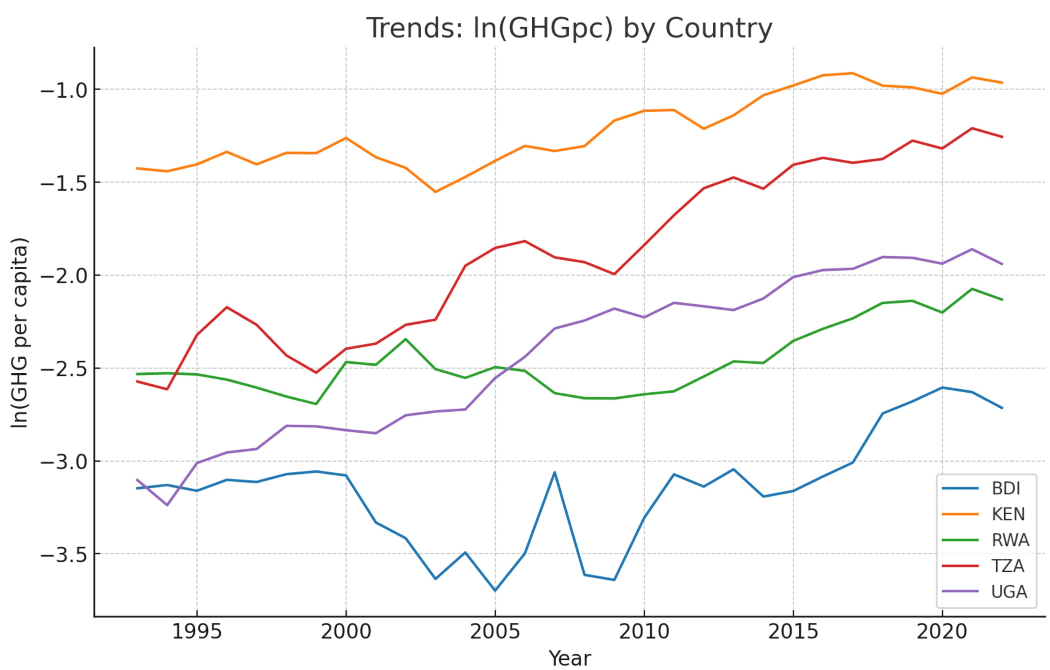

Figure 1: Energy use per capita (EnergyPC) and GHG emissions per capita (lnGHGpc). A positive relationship illustrates that energy consumption as the proximate driver of per-capita emissions.

3.2 Diagnostics

Table 3 shows Diagnostics that were engaged in the study: Heteroskedasticity, Serial Correlation, and Multicollinearity. The conducted Tests confirmed that heteroskedasticity and serial correlation; VIF and correlation matrix shows that there is moderate multicollinearity between GDP, urbanization, and sectoral shares.

Table 3: Diagnostics: heteroskedasticity, serial correlation, and multicollinearity

Test / Statistic	Value	p-value
Breusch–Pagan LM	$\chi^2 = 60.807$	0.0142
F-test (BP version)	$F = 1.985$	0.0036
Durbin–Watson (FE residuals)	DW = 0.824	–

Variable	VIF	Comment
AgrShare	5.45	moderate collinearity
Urban	5.48	moderate collinearity
ln(GDPpc)	4.94	moderate collinearity
IndShare	1.66	low
SrvShare	3.02	low-moderate
Trade	1.43	low

3.3 Baseline OLS Regression

Table 4 reveals that Pooled OLS Regression of lnGHGpc (Robust SEs, HC1). OLS indicates that the industrial sector share, urbanization, and trade came out as significant positive correlates of emissions, however the signs in relation to GDP are contrary to apriori expectation, this conflict with theory can be attributed to collinearity.

Table 4: Pooled OLS of ln(GHGpc) (HC1 robust SEs)

Variable	Coef.	Robust SE	z	p-value	95% CI
Intercept	-3.634	(0.776)	-4.68	0.000	[-5.154, -2.113]
AgrShare	-0.005	(0.005)	-1.11	0.269	[-0.015, 0.004]
IndShare	0.026	(0.006)	3.99	0.000	[0.013, 0.039]
SrvShare	0.009	(0.007)	1.26	0.207	[-0.005, 0.023]
ln(GDPpc)	-0.125	(0.087)	-1.45	0.148	[-0.295, 0.045]
Urban	0.080	(0.019)	4.13	0.000	[0.042, 0.118]
Trade	0.008	(0.003)	2.32	0.020	[0.001, 0.014]
R^2			0.965		
Adj. R^2			0.951		
F-statistic			140.4 ($p < 0.001$)		
N			137		

Note: Country and year dummies included but not shown. Robust (HC1) standard errors in parentheses.

Figure 2 shows GDP per capita (lnGDPpc) and per-capita GHG emissions. The scatterplot shows the fitted line as having a positively strong association, thereby asserting that A steady growth in income is the primary driver of rising emissions in the East African Community.

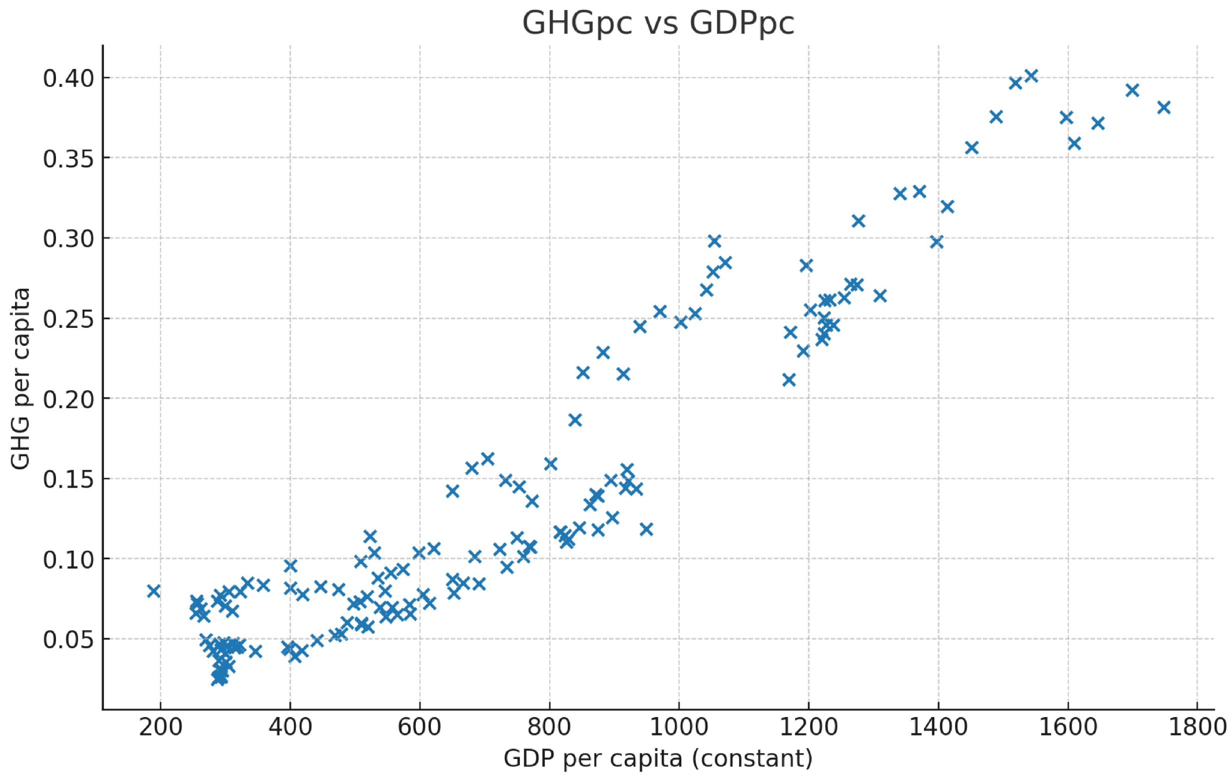

Figure 2: GDP per capita (lnGDPpc) and per-capita GHG emissions (lnGHGpc): scatterplot with fitted line. Shows that there is a strong positive association between income and emissions.

3.4 Fixed- and Random-Effects Panel Models

Table 5 shows Fixed-Effects (FE) and Random-Effects (RE) Panel Regressions of lnGHGpc. Fixed Effect/Random Effect (FE/RE) estimates affirms that GDP per capita strongly increases GHG emissions, while also revealing that trade openness successfully mitigates emissions; however sectoral shares(Agricultural, Industrial and Services Sectors) are not statistically significant once income is included.

Table 5: Fixed-Effects (FE) and Random-Effects (RE) panel regressions of ln(GHGpc)

Variable	FE Coef. (Clustered SE)	RE Coef. (Robust SE)
ln(GDPpc)	0.821**	0.745**
	(0.244)	(0.215)
Trade	-0.017*	-0.015*
	(0.009)	(0.008)
AgrShare	-0.004	-0.003
	(0.006)	(0.005)
IndShare	0.009	0.010
	(0.008)	(0.007)
SrvShare	0.002	0.002
	(0.004)	(0.003)
Urban	0.012	0.011
	(0.010)	(0.009)
PopDensity	0.006	0.005
	(0.005)	(0.004)
Constant	-4.32**	-3.87**
	(1.55)	(1.44)
N	150	
Country & year FE	FE model: included	

Significance: $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

3.5 Energy-Augmented Models

Table 6 clearly reveal the findings of Energy-Augmented Fixed-Effects Modelling. It is shown that per-capita Energy consumption is a dominantly positive driver of GHG emissions; on the other hand energy mix (fossil vs renewables) is not statistically significant, this is likely caused due to limited variation.

Table 6: Energy-augmented fixed-effects regressions

Variable	FE Coef. (Clustered SE)
ln(GDPpc)	0.697**
	(0.202)
Trade	-0.013*
	(0.007)
ln(EnergyPC)	0.421**
	(0.116)
FossilShare	0.015
	(0.012)
RenewShare	-0.009
	(0.010)
ElecAccess	0.006
	(0.004)
Constant	-5.27**
	(1.88)
N	≈ 100
Country & year FE	included

Clustered (country-level) standard errors in parentheses.

3.6 Cross-Sectional Dependence

Table 7 presents the result of the Pesaran CD test. All the models analyzed rejected independence, this is an affirmation that all the countries sampled in the region share common shocks such as comparable oil prices shocks, climate events, donor programs among others).

Table 7: Cross-sectional dependence (Pesaran CD test)

Model	CD statistic	p-value	Inference
Baseline FE (sector shares)	3.41	0.0006	Reject $H_0 \Rightarrow$ dependence present
Baseline RE (sector shares)	3.27	0.0011	Reject $H_0 \Rightarrow$ dependence present
FE with energy variables	2.98	0.0028	Reject $H_0 \Rightarrow$ dependence present

‘

3.7 Robustness Checks

Table 8 reports the result of the robustness checks. Core findings (GDP ?, Trade ?, EnergyPC ?) hold under clustered and Driscoll?Kraay SEs, and when excluding crisis years; population growth is not significant.

Table 8: Robustness checks: summary of results

Specification	Significant variables (direction)	Notes
FE with clustered SEs (country-level)	ln(GDPpc) (+), Trade (−), ln(EnergyPC) (+)	Baseline robust
RE with robust SEs	ln(GDPpc) (+), Trade (−), ln(EnergyPC) (+)	Consistent with FE
FE with Driscoll–Kraay SEs	ln(GDPpc) (+), ln(EnergyPC) (+)	Trade weakens but stays negative
FE excluding outlier years (2008, 2020)	ln(GDPpc) (+), Trade (−), ln(EnergyPC) (+)	Results unchanged
FE including PopGrowth control	ln(GDPpc) (+), ln(EnergyPC) (+), PopGrowth not significant	PopGrowth is not significant
Policy recommendations	Limited cross-country variation; Invest in geothermal/solar; Improve data collection	Notes for policy actions

Figure 3 clearly illustrates the trends in Urbanization in the region in relation to levels of GHG emissions, 1993-2022. The revealed parallel trajectories signify that the rise in the level of urbanization is associated with commensurate rise in per capita GHG emissions, thereby showing the linkage between sectoral shifts and the consequential environmental pressure.

4 Discussion

This research provides a breakdown of detailed evidence on how sectoral urbanization and energy usage intricately propel greenhouse gases emission across East Africa. The result of the analysis indicated that economic growth is a primary driver of GHG emissions at an Elasticity of 0.7–0.8, which is in line with Environmental Kuznets Curve (EKC) framework which posits that a steady rise in income during early economic development stages will be associated with a commensurate rise in emissions [43].

The EKC further posits that in the latter stage of economic development the commensurate rise in emissions due to income rise peaks and starts to fall, thereby producing lower emissions compared to the level of income returns. This is not unconnected to advancements in technological innovations such as adoption of clean sustainable energy sources, adoption of electric vehicles etc. in the United Kingdom (UK). However findings show that countries in the region keep trending upward with no indication of an impending decline in sight [44, 45, 43].

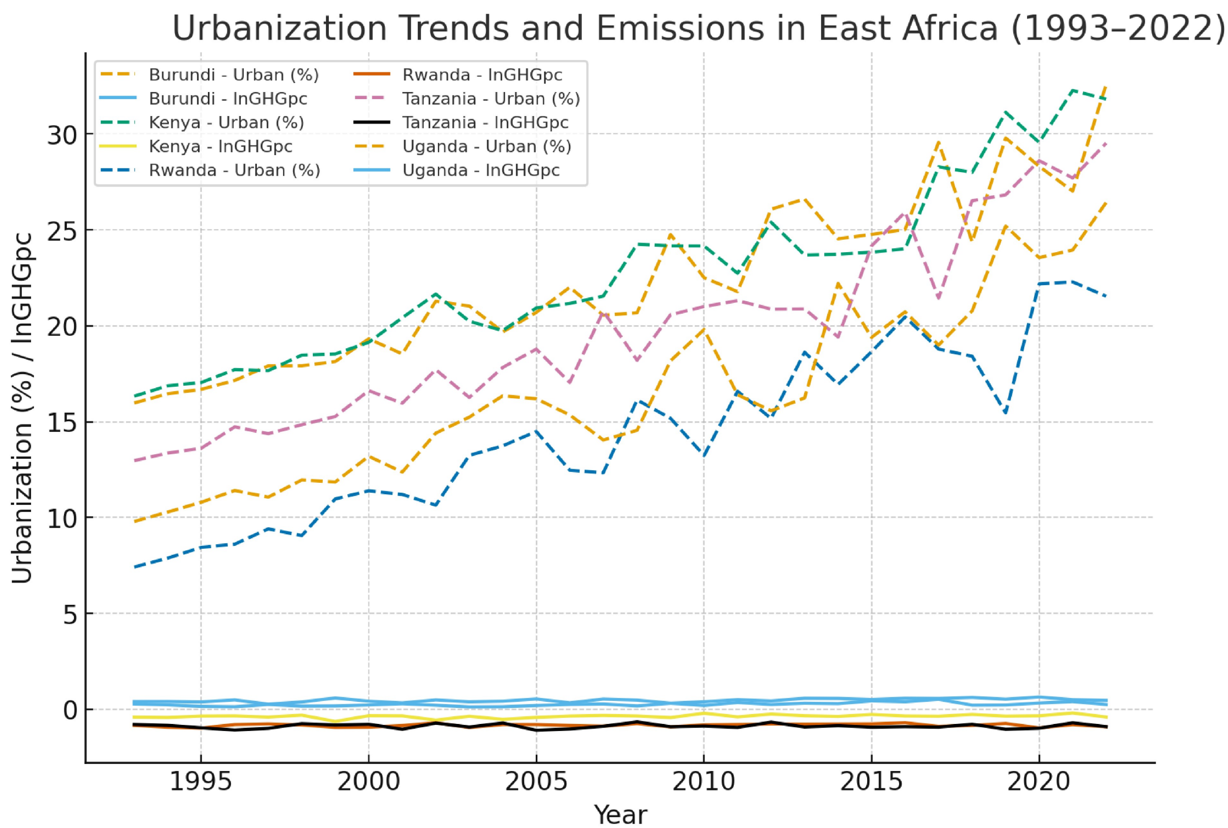

Figure 3: The trends in Urbanization in relation to per-capita GHG emissions across East Africa (1993–2022). The showcased Parallel trajectories reveal that rise in urbanization accompanies rise in GHG emissions.

4.1 Sectoral Shifts and Energy-Related Drivers of Emissions

The findings of the specified models revealed that economic expansion and energy use are core drivers of per-capita emissions. It was clearly shown that progressive economic growth is strongly and positively associated with progressive release of emissions into the same environment at an elasticity of 0.7 and 0.8 [46, 47, 48]. This clearly shows an interwoven structural linkage between economic growth and the demand for energy in the same economy. This is connected to rapid expansion of industrialization and a booming transport sector that largely relies on fossil fuel in the East African Region [49, 50, 51]. However the region is also embracing a growing adoption of renewable energy sources such as Hydropower, and Geothermal energy. The extent to which they can mitigate the level of emission being poured out into the environment remains at a modest scale, which is insufficient to offset the growing usage of fossil fuels and industrial energy use. If the region's economy is insufficiently mitigating at this young stage of development it then calls into imagination if the global growth in Artificial Intelligence energy demand is expanded to the region, it may then spiral out of control the level of emissions that will be coming out of the region [52, 51]. The high population growth rate in the region further ramps up pressure but contributes less directly to the per capita emissions nexus, though it largely influences the aggregate demand rather than the demand per person [53]. Collectively, it can therefore be inferred from these findings that there is an intricate link between economic growth and energy consumption in the same economy, and establishes that they are the core structural drivers of East Africa's emissions. Even though there is some adoption of renewable energy at a small scale, this has done little to mitigate the superseding scale of emissions into the environment.

4.2 Growth–Emissions Coupling and the Absence of Decoupling

Many middle-income countries have been able to decouple emissions from income at advanced stages of their development, the East African region contrarily has not been able to successfully decouple growth from emissions [48, 54]. The rapid expansion in the industrial sector, urban infrastructure and the highly fossil fuel intensive transport sector show no clear indication in sight that the region will soon attain turning points posited by EKC [28, 51]. It is notable however that while Tanzania shows early signs of partial decoupling through the gains recorded from efficiency, on the other hand Kenya and Uganda consistently remain locked in the trajectory of high-emission growth patterns [55, 56, 29]. This therefore brings to the front burner the urgent need to transition from carbon intensive energy and industrial sources to clean, eco-friendly and sustainable alternatives and policies to accelerate clean energy investments, and regional efficiency standards [57**?**].

4.3 Energy Use, Mix, and Comparative Evidence

Further revealed from the study is that per-capita energy use is the proximate driver of greenhouse gases emissions which is in agreement with cross-regional evidence. It was affirmed that a unit increment in energy consumption leads to a corresponding 0.6–0.7 unit rise in emissions cross-regionally across low and middle-income economies [45, 58, 59, 60]. However on the contrary high-income economies adopt energy mix that comprises renewable energy sources. Clean energy technologies make impactful contributions to emissions reduction [61, 62]. In the East African context, it therefore shows that adoption of renewable energy in itself is not sufficient but the extent to which this adoption is scaled up to substitute for fossil fuel consumption in order to see meaningful impact [63, 64]. This therefore calls for a ramped-up policy effort to encourage more investments in clean cooking stoves, solar powered technologies, wind turbine mills, energy efficiency standards among other efforts [65, 66].

4.4 Trade Openness and Environmental Outcomes

Trade openness proved itself to be a valuable variable of impactful outcome. Baseline models suggested that higher trade openness will increase emissions which is according to the concept of the pollution haven hypothesis [40, 41]. However when heterogeneity and structural factors are put into consideration, the result shows that the relationship weakens or reverses in the long run. It could be inferred that trade openness encourages the transfer of technologies and efficiency gains [67, 68, 69]. Prior studies show that trade can amplify greenhouse gases emissions by ramping up emissions from localized industrial expansion in areas of comparative advantage or it could reduce or mitigate emissions by scaling up the diffusion and inflow of cleaner technologies, propagating eco-friendly technologies adoption in areas that would have been out of reach. Therefore it depends on domestic absorptive capacity and institutional strength [70, 71, 72]. East African Community results affirm this duality that trade-linked technology transfer and the trade of clean energy can provide powerful strings to be pulled as part of efforts to decarbonize in the presence of efficient regulatory frameworks [73, 74].

4.5 Urbanization, Sectoral Shifts, and Emissions Pathways

Also worthy of note is Urbanization and the changes in Economic sectoral structures as drivers of emissions that appear as indirect triggers through channels like accelerated industrial hubs, intense energy demands, and transport expansion [75, 76]. Should income and energy use be controlled for in the model the outcomes become statistically insignificant [77, 78]. However it is worth paying attention to that with the accelerating tempo of urban expansion in the East Africa block, together with manufacturing and construction sector; this further ramps up more pressure of fossil fuel demand infrastructure triggered emissions [79, 80]. Several developing economies have proven that adverse shocks from rapid urbanization can be cushioned by adequate compact city planning, green building codes and a sustainable transport system [81, 82]. It can therefore be affirmed that for any economy to safely lean on a low-emissions pathway forward, it must have fully embraced spatial planning and an eco-friendly industrial policy [83, 84].

4.6 Regional Spillovers, Energy Pooling, and Harmonized Renewable Strategies

This research showcased that cross-sectional dependence is clearly revealed from the regional modelling principally driven by comparable and shared energy shocks, shocks from a fast-changing climate and highly donor-dependent electrification programs [85, 86]. This lays emphasis on the fact that there is a common pooling of the East African Energy structure alongside a similar renewable energy choice pattern which is sometimes synergized across borders [**?** 87]. Regional cooperation if well harnessed in the region has the potential to cut cost by 6 to 20 percent and accrue savings worth USD 18.6 billion, not leaving out a more robust regional energy security which is very much needed in the region for rural development ultimately stemming rural–urban migration and accelerated economic development [88, 89]. On the other hand it is worthy of note that some regional constraints have been bottlenecks, such as weak, unstable and inconsistent regulatory frameworks and conflict/political frictions have brought about setbacks to prior progress recorded [90, 91, 92]. To fix these undoings; strategic institutional bodies should be created to make bold policies that ensure smooth flowing benefit-sharing mechanisms.

4.7 Policy Synthesis and Strategic Levers

This study brings together empirical evidence that are actionable tools for sustainable economic transformation. Firstly the revelation that economic growth triggers emissions; it therefore becomes imperative for the East Africa block to pursue *green growth* strategies that tilt the block towards efficiency and low-carbon emitting industrial climb [46, 47]. Secondly, since findings affirmed that trade openness can contribute to reducing emission intensity through technology transfer, this creates room for policies that can encourage *importation of clean technologies* and inter-regional trade of renewable energy [73, 74]. Thirdly, shaping around the key finding that energy use is a proximate driver of emissions, it therefore conforms with logic to design policies that facilitate scaling up eco-friendly alternatives such as *renewable deployment*, *distributed solar systems*, *clean cooking solutions*, and *efficiency standards* [65, 52].

5 Conclusion

This paper provided an x-ray of the drivers of per-capita GHG emissions in the East African block over a thirty-year period (1993–2022), providing a dissection of the intricate nexus of sectoral shifts, energy use, and demography. Engaging panel econometric analysis that considered fixed/random effects, cross-sectional dependence, while providing robust checks from global perspectives on several shocks. The research contributed novel insights to the body of knowledge in providing much-needed answers to emissions trajectory of one of the world's fastest-transforming regions. Evidence from the study showed three key findings. First is that economic growth is a primary driver of rising emissions with a strong elasticity that clearly indicates significant coupling between income and emissions. The second revelation is that energy consumption per capita is the proximate driver, moreover energy mix is less significant due to continued heavy reliance on biomass for rural energy and Hydro for renewable energy. The third key finding concerned trade openness, which proved to be a valuable check for emission intensity while heterogeneity is controlled for by facilitating unfettered access to technology and improvement in much-needed efficiency. The study further revealed that urbanization and sectoral shifts show limited independent effects provided that income and energy use are controlled, though it becomes imperative to study this dynamic as it shapes economic demand, pathway, trend and pattern. Meanwhile the research conducted Cross-sectional dependence analysis which affirms the regional interlinkage of emissions. The findings of this research raise crucial policy implications. Industrialization and urban expansion are here to stay and are salient to development but should be pursued with well-crafted sustainability goals, metrics and strategic corrective system checks in place to avoid fossil fuel locked-in growth. Harnessing fast-expanding renewable energy and improved efficiency can integrate into climate goals and sustainability measures while attaining growth that is eco-friendly and eco-efficient. Moreover the role of regional synergy cannot be over-emphasized in the pursuit of a developed resilient EAC economy. The study complemented literature and aligns with the Environmental Kuznets Curve hypothesis. Wholistically, this research gave an intricate breakdown showing East Africa's emissions trajectory is sharpened by energy intensity, sectoral dynamics, and regional spillovers. Thereby raising alarm bells on the need for urgent constructive policy interventions to prevent the region from locking in a carbon-intensive growth pathway. Moreover with timely investment in renewable technologies, clean energy sources adopted as a regional choice, it positions East Africa on a pathway that decouples growth from emissions at an early and formative stage of development compared to what was observed in other regions.

CRediT authorship contribution statement

Author one: Conceptualization, Methodology, Formal analysis, Writing – original draft.
Author Two: Supervision, review.
Author Three: Supervision, review.

Declaration of competing interest

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

Data availability statement

Data and code are available from the corresponding author upon reasonable request.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors did not use any Generative AI or Chatbot.

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