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# Energy intensive growth and the transition pathways: Insights into the role of renewable energy and open market conditions in developing countries

Festus Victor Bekun [a,b,c], Michael Provide Fumey [d], Marcin W. Staniewski [b], Lipeng Sun [e,*], Philips O. Agboola [f]

[a] Faculty of Economics Administrative and Social sciences, Istanbul Gelisim University, Istanbul, Turkey
[b] University of Economics and Human Sciences in Warsaw, Poland
[c] Research Center of Development Economics, Azerbaijan State University of Economics (UNEC), Baku, Azerbaijan
[d] School of Public Policy and Administration, Northwestern Polytechnical University, Shaanxi Province, Xi'an, China
[e] School of Management, Wenzhou Business College, Wenzhou, 325035, China
[f] Division of Engineering, Howard Payne University, Brownwood, TX, 76801, USA

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ABSTRACT

This study examines the impact of economic growth, renewable energy consumption, and open market conditions on energy intensity across 34 developing countries from 1999 to 2022 using the method of moments quantile regression. By analysing how these factors influence energy intensity across different quantiles, the study provides insights into the heterogeneous nature of these relationships. The results reveal a positive and statistically significant impact of economic growth per capita on energy intensity across all quantiles, with a more substantial effect at higher energy intensity levels. However, the squared term of economic growth per capita exhibits a negative and significant influence, confirming the presence of an inverted U-shaped relationship. Renewable energy consumption reduces energy intensity significantly across all quantiles, with more potent effects at higher quantiles. This indicates that economies with higher energy intensity benefit more from transitioning to renewable energy sources. Market freedom initially contributes to higher energy intensity. However, its impact diminishes at higher quantiles, suggesting that while economic liberalisation may increase energy consumption in the short run, it can promote efficiency improvements over time. These findings highlight the need for differentiated policy approaches, where economies with lower energy intensity focus on balanced growth strategies. In comparison, those with higher energy intensity prioritise aggressive renewable energy integration and efficiency-enhancing policies. The study underscores the importance of adopting tailored energy policies that consider the varying impacts of economic and policy variables across different energy intensity levels to achieve sustainable energy transitions.

## 1. Introduction

Universal energy consumption (EC) is steadily rising, and it is one of the most pressing challenges in the twenty-first century, given its significant consequences in global warming and climate change [1–3]. Since 1995, the International Energy Agency (IEA) has observed a 50 % rise in worldwide EC (IEA, 2024). Emerging nations account for most of this growth, owing to their intense economic activity and industrialisation stage. As part of its green growth initiative, the United Nations (UN) has regarded a global pledge from all nations to ensure more vital access to adequate, affordable, clean energy supplies to reduce climate change concerns. In this context, Sustainable Development Goals 7 (SDG-7) and 13 (SDG-13) are implemented, which focus on energy efficiency and clean energy intake in the overall energy portfolio [4]. Several international commitments and conferences, like the United Nations Framework Convention on Climate Change (UNFCCC), Paris Agreement–COP 21, and COP26, have been assembled to grab the attention of leading contributors to climate change action. These agreements emphasised the need for energy-intensive growth through clean energy rather than energy from polluting sources, which helps mitigate climate change and ecological devastation.

Efficient energy production and use are imperative for energy

* Corresponding author. School of Management, Wenzhou Business College, Wenzhou, 325035, China.
*E-mail addresses:* fbekun@gelisim.edu.tr (F.V. Bekun), fumeymichael3@gmail.com (M.P. Fumey), m.staniewski@vizja.pl (M.W. Staniewski), lipengsun16@gmail.com, sunlipeng2019@163.com (L. Sun), Pagboola@hputx.edu (P.O. Agboola).

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sustainability and economic progress [5,6]. The reduction of energy intensity (EI) via more significant energy efficiency (EE) is a worthwhile endeavour [7,8]. Thanks to a mixture of energy policies, open market attractiveness, and novelty in clean energy technologies, global EE increased by 13 % between 2000 and 2016. As a consequence of the SDGs and COP26, EI is receiving a plethora of attention from policymakers and officials from most nations around the globe. The extent of energy needed to make a unit of GDP is referred to as EI [9]. Put another way, "a greater EI implies a higher expense of converting energy into every unit of GDP" [8]. The drivers of EI are a requisite discussion for economic cooperation because energy is directly proportional to the amount of energy transformed into economic progress [10]. This study incorporates EI into the deliberation in the context of African countries, attempting to uncover the factors that drive it in an era of energy transition, decarbonisation and open markets.

Within the African context, fast economic growth was often in tandem with development models requiring more energy; consequently, this has placed a heavy toll on the energy systems already in use while aggravating environmental problems [11,12]. Despite immense renewable energy (RE) potential, many African nations continue to grapple with significant hurdles, including limited infrastructure, high capital costs and regulatory restrictions, all of which prevent a shift towards cleaner energy solutions. This study discusses the role of RE and the open-market conditions that would allow for sustainable growth in Africa while generating insights on how these dynamics can constitute support towards a development pathway that is both environmentally and economically sustainable for the continent's future.

Given the rising trajectory of energy consumption (EC) and energy intensity (EI) in high-energy output and higher income per capita in this continent, the issue has piqued the interest of energy experts and policymakers [13]. Despite Africa's tiny fraction of global $CO_2$ emissions, the continent continues to see an increase in emissions due to significant resource extraction and energy usage [14]. By 2040, Africa's urban populace will rise to half a billion, significantly quicker than China's urban populace in the previous two eras [15]. As the urban populace rises, so does the demand for energy for industrial output, and Africa unfolds as a prominent player in the worldwide oil and gas markets [16].

Africa's expanding influence is also evident in natural gas markets, as the continent has surpassed China as the world's third-largest source of gas demand. As a result, the world population lacking energy access is becoming highly concentrated, with 90 % of those without electricity and almost half of those without clean cooking access residing in Africa by 2040 [15]. Africa's energy destiny depends on how it satisfies its expanding energy demands; thus, increasing the EI is perilous for long-term energy security and eradicating energy poverty. As a result, enabling fast automation, closing the energy gap and limiting the impacts of GHG emissions through introducing EI is a top priority for African economies, which ultimately boosts their clean growth programmes.

While EI depends on the stage of economic expansion, integration of new technologies, and capital investment, various drivers positively or negatively impact it. Empirical research suggests that open economies expand quicker than closed nations [17]. In open states, a state concentrates on sectors with a competitive advantage. However, if the regulators do not contemplate tight control of energy conservation techniques, this eventually harms environmental quality [18]. Although we now have a better knowledge of the relevance of the development of markets, their role is still frequently overlooked [19], particularly in African countries in the context of EI. Suppose individual freedom in finance, investment and trade are not perfectly integrated. In that case, they cannot be regarded as an open market, and the market will not operate efficiently, affecting energy conversion. However, there is a lack of debate on whether the market structure is conducive or deleterious to EI.

SDG7 urges a considerable surge in the share of renewable energy use in the energy mix [20]. Only 18 % of the world's total primary energy consumption was covered by renewables in 2018. More crucially, it will take time to establish the necessary technologies to enable global economies to lower the EI. As a result, transitioning from unclean energy sources to renewable might offer the necessary buffer time to lower the EI level. Despite the overwhelming evidence that RE leads to decreased EI, the percentage of RE in developing nations, notably in Africa, remains minimal [21,22].

In terms of novelty and addition to the present body of knowledge, this is the pioneer multi-country research on the drivers of EI in Africa, as far as we know, conducted within the context of the open market idea. While African nations are predominantly low-income economies, the open market framework in the context of EI is essential, as they face multiple trajectories of emission-green growth energy. The significance of RE and economic growth in improving EI in African economies is still to be fully explored. Besides, the impact of market structure on EI in African countries has never been investigated. We scrutinise the effect of economic growth, RE, and open markets (financial, investment, and trade freedom) on EI in African economies to fill the gaps left by prior energy literature. We employ a unique technique to assess the asymmetric impacts across chosen time-series variables using a panel dataset of African economies from 1999 to 2018 to accomplish these objectives. Second-generation cointegration tests determine whether there is a long-run link among the constructs of interest. We used the fixed effects model with robust standard errors [23]. Then, we examined distributional effects employing the recently devised method of moments quantile regression (MM-QReg) procedure. Finally, the outcomes of this study will help African countries design suitable energy policies to minimise EI and enhance energy usage efficiency.

The rest of the paper is structured as follows: Section Two encapsulates the literature review; Section Three presents the data source, empirical modelling and techniques, while Section Four covers the results and discussion, with Section Five covering the conclusions, policy recommendation, limitations and future research suggestions.

## 2. Literature review

Recently, researchers have been paying more attention to the significance of EI in changing environmental quality [6,24]. However, in the extant literature, the determinants of EI were given less priority, even though they must be addressed to meet the SDGs and the COP26 goal regarding accessible clean energy and reducing energy poverty [25, 26]. In the prior research, economic growth (EG), structural changes, innovative technologies, investments, institutional changes and energy prices are all drivers that affect EI or EF (energy use per unit GDP) [8, 27].

Theoretically, the environmental Kuznets curve (EKC) [18] and institutional theories [28] examine the interactive relationship between economic growth (pgdp), energy intensity (EI), and renewable energy (RE) adoption in Africa. The EKC theory posits that GDP may raise EI in the short term. However, the income level can cause a shift in energy practices towards sustainability, reducing energy use per unit of economic activity. Concurrently, institutional theory speaks to the essentiality of market systems and conditions of freedom for finance, investment and trade (TRDF) in determining how far countries go in introducing cleaner energy sources. The junction of these two schools of thought provides an understanding of how economic growth and institutional factors can either facilitate or impede the African transition to energy-efficient and renewable energy-driven pathways, minimising energy intensity and achieving sustainable development.

Empirically, studying the link between EG and EI is critical because better EI results in higher productivity, which leads to enhanced EG. However, study on the link between EI and EG is limited. Studies addressing the opposite link between how economic expansion affects EI are particularly scarce in the African setting. Kepplinger et al. [29] use mixed-effect models to examine the causes of EI in the manufacturing industry in both OECD and non-OECD nations. GDP is adversely correlated with Rajbhandari and Zhang [30], who looked at the causal link between EI and EG in the case of 56 middle-income states from 1978 to 2012. Lower EI and better EG are found to have a bidirectional causal relationship.

However, substantial prior studies referred to the EE as the same as EI, using the same proxy (energy use per unit GDP), and indicated a strong effect of EG on the EE. In a study, Sineviciene et al. [24] found that a rise in EG promotes EE. Studies involving a blended sample of economies have identical issues, with results that support or refute each other. For instance, Rajbhandari and Zhang [30] demonstrated that unidirectional causality runs from EG to EE in high-income nations. However, a bidirectional causality is found in middle-income states, whereas Mahmood and Kanwal [31] revealed that no causality runs from EE to EG, but causality exists from EG to EE. Another recent research by Bataille and Melton [32] looks at the effect of EE on Canada's EG between 2002 and 2012. According to studies, improved EE leads to better GDP. Samargandi [6] discovered that the coefficient of EG has an adverse and momentous result on EE for OPEC countries, implying that OPEC economies obtain EE as the number of economic activities rises.

GDP usually bears some negative effect on energy intensity, implying that with the increase in income level, energy efficiency is gained by the economy [33]. This phenomenon can be observed in ASEAN countries and the European Union, where high income levels mean low energy intensity [34]. In Indonesia, renewable technology is crucial in reducing energy intensity, thus ensuring sustainable economic development.

Trade openness usually reduces energy intensity in some ways by improving energy supply and transferring technology [33]. This effect can be noted in the EU and Ghana, where energy intensity decreases with trade liberalisation [35]. However, trade openness within the context of ASEAN does not have a significant effect [34]. While fewer studies emphasise the direct impact of financial and investment freedom on energy intensity, the reports indicate that foreign direct investments (FDI) in Indonesia affect energy intensity positively, thus prompting the assumption that more FDI could lead to higher energy consumption [36].

The increasing concern for RE and its impact on EG and environmental quality has spurred a vigorous discussion over the last two decades [37]. RE usage is acknowledged as significantly influencing the atmosphere by reducing $CO_2$ emissions in the atmosphere [38]. As a result, boosting RE use improves environmental quality and contributes to developing a clean and green climate framework. On the other hand, RE consumption significantly influences the EI in many economies and environmental settings. For example, the impacts of RE on EI are researched utilising panel data from 30 Chinese provinces spanning 2000 to 2018, and it is discovered that RE development considerably helps to lower EI in China [39,40]. Yu et al. [41] inspected the impacts of RE growth on EI in 82 significant nations using a dynamic panel threshold valuation procedure. The study revealed that RE expansion has a considerable detrimental influence on EI. Three internal Chinese economic elements (technology advancement, economic structure and energy usage framework) impact EI. In contrast, clean energy usage reduces EI [42]. RE was found to have considerably impacted raising the proportion of EI in ECOWAS member nations [43]. Hence, the impact of RE consumption on EI provides diverse results, necessitating more research using a comprehensive econometric model.

Several other earlier researches investigated factors such as technical innovation, FDI and trade openness [6,44–46] for the sake of EI drivers. Some research has found a long-term relationship between EI and pollution [47–49]. However, none of the prior studies focused on open market systems in terms of financial, investment, and trade freedom and their impact on EI in any country or region. To bridge that gap, this study adds a new variable to the ongoing discussion of EI for the African continent, which desperately needs research in the context of energy since it is grappling with the energy-intensive growth paradigm.

## 3. Empirical methodology

### 3.1. Model specification

Energy intensity (EI), measured as energy consumption per unit of GDP, is a critical indicator of energy efficiency in an economy. This study is theoretically grounded in the environmental Kuznets curve (KC) hypothesis, which posits a nonlinear relationship between economic growth and impact indicators [50,51]. At the initial stages of economic development, industrialisation and expanding production activities lead to increased energy consumption, raising energy intensity [50]. However, economies undergo structural transformations as income levels rise, shifting from energy-intensive industries to service-based and technology-driven sectors that rely on more efficient energy systems [51,52]. Advancements in energy-efficient technologies, regulatory policies and sustainable practices further contribute to the eventual decline in energy intensity [50]. These variations follow the algebraic form:

$$lnEI_{i,t} = \varphi_0 + \varphi_1 lnPgdp_{i,t} + \varphi_2 \, ln \, PgdpSQ_{i,t} + \varphi_3 Z + \varepsilon_{i,t} \tag{1}$$

where EI represents energy intensity, measured as energy consumption per unit of GDP, indicating energy use efficiency in an economy. Pgdg and PgdgSQ denote GDP per capita and its squared term, respectively, while Z captures additional influencing factors, specifically, the effects of renewable energy transition and open market dynamics are introduced in this study. The expanded model follows this algebraic formulation:

$$lnEI_{i,t} = \varphi_0 + \varphi_1 lnPgdp_{i,t} + \varphi_2 \, ln \, PgdpSQ_{i,t} + \varphi_3 lnRE_{i,t} + \varphi_4 lnMrkF_{i,t} + \varepsilon_{i,t} \tag{2}$$

In Eq. (2), RE denotes the shift to renewable energy, while MrkF represents open market systems. A negative $\varphi_3$ indicates that as economies increase their reliance on renewable energy, they experience cleaner and more efficient energy conversion, thereby reducing energy intensity [41]. Similarly, a negative $\varphi_4$ would suggest that open market dynamics facilitate access to capital, enabling the adoption of energy-efficient technologies and infrastructure [53].

Further empirical steps can provide valuable insights for policy and extend the existing literature. First, open market systems encompass various economic dynamics, each component playing a distinct role in the energy transition. Theoretically, it is argued that financial freedom enables better capital allocation for cleaner technologies, while investment freedom attracts foreign and domestic investments in energy-efficient infrastructure [54]. Trade freedom improves access to advanced energy-efficient technologies and fosters competition, which drives efficiency improvements [54]. To extend Eq. (2), MrkF is disaggregated into the specific sub-indicators:

$$lnEI_{i,t} = \varphi_0 + \varphi_1 lnPCgdp_{i,t} + \varphi_2 \, ln \, PCgdpSQ_{i,t} + \varphi_3 lnRE_{i,t} + \varphi_4 lnFinF_{i,t} + \varphi_5 lnINVF_{i,t} + \varphi_6 lnTRDF_{i,t} + \varepsilon_{i,t} \tag{3}$$

FinF denotes financial freedom, INVF stands for investment freedom, and TRDF refers to trade freedom. In line with the literature, the relationship between market freedom and energy intensity may not be strictly linear [50,52]. Regulatory inefficiencies may hinder energy efficiency improvements at lower levels of market openness. However, at higher levels, excessive liberalisation could lead to over-reliance on energy-intensive industrial expansion. Therefore, achieving a policy balance is crucial. An alternative specification is used to assess the combined impact of open market freedom with a nonlinear term:

$$lnEI_{i,t} = \varphi_0 + \varphi_1 lnPgdp_{i,t} + \varphi_2 \, ln \, PgdpSQ_{i,t} + \varphi_3 lnRE_{i,t} + \varphi_m lnMrkF_{i,t} + \varphi_{mq} lnMrkFSQ_{i,t} + \varepsilon_{i,t} \tag{4}$$

The introduction of MrkSQ in Eq. (4) allows for capturing both efficiency-enhancing and potentially adverse effects, offering a more complex understanding of how open market conditions influence energy intensity. The expected shapes and implications are as follows: If $\varphi_m > 0$ and $\varphi_{mq} < 0$, the relationship is inverted U-shaped, suggesting that beyond a certain threshold, market liberalisation could reduce energy intensity [50]. On the other hand, if $\varphi_m < 0$ and $\varphi_{mq} > 0$, the relationship is U-shaped, indicating that open market conditions initially reduce energy intensity, but beyond a certain point, the effect could reverse and increase energy intensity [50].

### 3.2. Data description

The variables, their definitions, data sources and basic descriptive statistics are summarised in Table 1. The data panel constructed for this study includes 34 African countries from 1999 to 2022, selected strictly based on data availability. In particular, the selection criterion was influenced by the availability of open market indicators, which are not consistently reported for some countries. To ensure the robustness of the analysis, countries with incomplete data on key variables were excluded, thereby maintaining the integrity of the dataset. A detailed list of the selected countries is provided in Table A1, attached in the Appendix.

A crucial aspect of the data description that is important for shaping the empirical steps is the normal distribution of the variables. The results of the normality tests, as summarised in Table 2, indicate that the data series for the variables do not follow a normal distribution. This has significant implications for the empirical methodology, necessitating an approach that goes beyond standard assumptions of normality.

### 3.3. Econometric steps

#### 3.3.1. Cross-section dependence (CSD) test

It is more probable that the information from the studied nations shows connections due to their trade links and other economic activity. Thus, we considered the bias-corrected LM test by Ref. [55–58] whose equivalences may be stated as:

$$y_{it} = a_i + \beta_{,1} X_{it} + \mu_i \text{ for } i = 1, 2, 3 \ldots N; t = 1, 2, T \tag{5}$$

where $X_{it}$ and β are estimators and coefficients represented as vectors. They predict $a_i$, which signifies individual time-invariant factors. The null premise states that $u_{it}$ is independent and identically spread across time and cross-sectional units; alternatively, cross-sections might be correlated with $u_{it}$. However, the absence of serial correlation remains unchanged. Therefore, the fundamental principle is that:

$$H_0 : ij = \rho_{ji} = cor\left(\mu_i, \mu_{jt}\right) = 0 \text{ for } i \neq j \text{ and } H_0 : ij = \rho_{ji} \neq 0 \text{ for } i \neq j \tag{6}$$

Whereas $\rho_{ij}$ is the condition value of the product moment shown by

**Table 2**
Tests for normality.

| Panel A: | Observations | Skewness/Kurtosis tests | | | |
|---|---|---|---|---|---|
| Variables | | Pr (Skewness) | Pr (Kurtosis) | adj chi2 (2) | Prob > Chi2 |
| *ln*EI | 816 | 0.905 | 0.000 | 17.96[a] | 0.000 |
| *ln*Pgdp | 816 | 0.000 | 0.000 | 82.44[a] | 0.000 |
| *ln*RE | 816 | 0.000 | 0.000 | 193.65[a] | 0.000 |
| *ln*MrkF | 816 | 0.000 | 0.000 | 236.25[a] | 0.000 |
| *ln*FinF | 816 | 0.000 | 0.000 | 288.76[a] | 0.000 |
| *ln*INVF | 816 | 0.000 | 0.000 | 287.02[a] | 0.000 |
| *ln*TRDF | 816 | 0.000 | 0.000 | 1435.02[a] | 0.000 |
| **Panel B:** | | Shapiro-Francia W′ test for normal data | | | |
| | | W' | V' | z | Prob > z |
| *ln*EI | 816 | 0.980 | 10.943 | 5.128[a] | 0.000 |
| *ln*Pgdp | 816 | 0.940 | 33.472 | 7.232[a] | 0.000 |
| *ln*RE | 816 | 0.740 | 145.410 | 9.747[a] | 0.000 |
| *ln*MrkF | 816 | 0.914 | 48.150 | 7.880[a] | 0.000 |
| *ln*FinF | 816 | 0.866 | 74.812 | 8.643[a] | 0.000 |
| *ln*INVF | 816 | 0.888 | 62.229 | 8.331[a] | 0.000 |
| *ln*TRDF | 816 | 0.507 | 275.855 | 10.763[a] | 0.000 |

[a] $p < 0.01$ implies the rejected normality condition.

$$\rho_{ij} = \rho_{ji} = \frac{\sum_{i=1}^{T} \mu it, \mu jt}{\left(\sum_{i=1}^{T} \mu it^2\right)^{1/2} \left(\sum_{i=1}^{T} \mu it^2\right)^{1/2}} \tag{7}$$

With N, the number of possible unions $(u_{it}, ujt)$ increases

$$LM = T \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \hat{p}^2 ij \tag{8}$$

Whereas $\hat{p}^2 ij$ is a sample estimation of the remaining correlational sets

$$\hat{\rho} ij = \hat{\rho} ij = \frac{\sum_{i=1}^{T} \hat{u} it, \hat{u} jt}{\left(\sum_{i=1}^{T} \hat{u} it^2\right)^{1/2} \left(\sum_{i=1}^{T} \hat{u} jt^2\right)^{1/2}} v \tag{9}$$

Moreover, $\hat{u} it$ reflects the estimate of $u_{it}$. The LM statistic has $\frac{N}{(N-1)/2}$ degrees of freedom and an asymptotically distributed φ2 distribution under the null hypothesis. However, when N is significant, and T is finite, this test may encounter extensive magnitude pre-judices, a usual worry in analytical contexts, notably when LM statistics are not correctly adjusted for finite T. With a huge N, the danger for bias may grow. An alternate strategy was offered to solve this.

$$CSD = \sqrt{\frac{2T}{N(N-1)}} \left(\sum_{j=1}^{N-1} \sum_{j=i+1}^{N} \hat{\rho} ij\right) \tag{10}$$

The output discusses the cross-sectional dependence (CD) statistic and its properties in a panel data framework. It states that the CD statistic follows a standard normal distribution under the null hypothesis. In non-stationary models and homogeneous/heterogeneous dynamic processes, the CD statistics exhibit an actual mean of zero when the time

**Table 1**
Summary description of variables.

| Variables | Definition | Data Sources | Mean | Minimum | Maximum | Std. Dev |
|---|---|---|---|---|---|---|
| EI | Energy consumption per GDP (1000 Btu/2015$ GDP PPP) | U.S Energy Information Administration (eia) | 2.204 | 0.217 | 9.652 | 1.566 |
| Pgdp | GDP per capita (constant 2015 US$) | Database, World Bank (WDI) | 2142.91 | 250.24 | 13048.07 | 2335.67 |
| RE | Renewable energy consumption (% of total final energy consumption) | World Development Indicators (WDI) Database, World Bank | 61.599 | 3.700 | 95.800 | 28.552 |
| FinF | Index of financial Freedom | Heritage Foundation | 44.301 | 10.000 | 70.000 | 14.081 |
| INVF | Index of Investment Freedom | Heritage Foundation | 49.412 | 0.000 | 90.000 | 15.047 |
| TRDF | Index of Trade freedom | Heritage Foundation | 63.241 | 0.000 | 89.000 | 12.044 |
| MrkF | Index of Open Market economy based on the average index of Financial, Investment and Trade freedom | Heritage Foundation | 52.318 | 11.700 | 82.667 | 10.755 |

length (T) and cross-sectional units (N) take on specific values, in contrast to the Lagrange multiplier (LM) statistics. Standard valuation approaches will likely suffer from bias in the context of homogeneous and heterogeneous dynamic models. However, the CSD procedure remains crucial because, due to the low model bias of the factor background, the FE/RE residua will have an exact mean of zero even for fixed T, given a symmetric distribution of disturbances. Pesaran [57] proposes an improved version to handle unbalanced panel data conditions:

$$CSD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{j=1}^{N-1}\sum_{j=i+1}^{N}\sqrt{T_{ij}}\ \widehat{\rho}ij\right) \tag{11}$$

Whereas $T_{ij} = \#\ (T_i \cap T_j)$ (observations units i and j in a time series),

$$\widehat{\rho}ij = \widehat{\rho}ij = \frac{\sum_t \epsilon T_i \cap T_j(\widehat{u}it - \widehat{u}i)(\widehat{u}jj - \widehat{u}j)}{\left\{\sum_t \epsilon T_i \cap (\widehat{u}it - \widehat{u}i)^2\right\}^{1/2}\left\{\sum_t \epsilon T_i \cap T_i(\widehat{u}it\widehat{u}jj)^2\right\}SS^{1/2}} \tag{12}$$

and

$$\widehat{u}i = \frac{\sum_t \epsilon T_i \cap T_j, \widehat{u}it}{\#(T_i \cap T_j)} \tag{13}$$

The modified equation indicates that the balances for specific subdivisions t are not uniformly equal to nil. Consequently, Breusch and Pagan [56] suggest utilising the CSD approach within the LM framework to address issues related to cross-sectional dependency (CSD). The panel data formulation for performing the Breusch-Pagan LM test is expressed as:

$$y_{it} = a_i + \beta_1 X_{it} + \varepsilon_{it} \tag{14}$$

In this panel data set, the subscripts i = 1, 2, and N represent the cross-sectional dimension (e.g., countries), while t = 1, 2, and T signifies the period length. $X_{it}$ represents the explanatory factors in a $k\times$ 1 path form, and alpha and $a_i$ correspond to the individual intercepts and slope coefficients across the cross-sectional units. Consequently, the underlying assumptions for employing the Breusch-Pagan LM approach to assess for CSD can be summarised as follows:

$$LM = \sum_{i=1}^{N-1}\sum_{J=i+1}^{N} T_{ij}\ \widehat{\rho}ij \rightarrow X^2\frac{N(N-1)}{2} \tag{15}$$

The link coefficient $\widehat{\rho}ij$ is attained from independent ordinary least squares (OLS) regressions. The Breusch-Pagan (B-P) LM assessment evaluates the presence of CSD, where the covariance among the error terms $\mu_{it}$ and $\mu_{jt}$ is zero for all t and $\neq j$. The other hypothesis is that the covariance is non-zero for at least one pair of $i \neq j$ indicating the presence of CSD. This bias-adjusted assessment is known as the Pesaran LM assessment, and the calculated test statistics for this test are provided:

$$LM = \left(\sqrt{\frac{2}{N(N-1)}}\right)\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\widehat{\rho}ij\ \frac{(T-K)\widehat{\rho^2}ij - \mu}{\sqrt{v^2 T_{ij}}} \rightarrow N(0,1) \tag{16}$$

where k denotes the number of repressors and $\mu T_{ij}$ and $v^2 T_{ij}$ represents the precise mean and variance of $(T-K)\widehat{p}^2 ij$.

### 3.3.2. Unit roots test and cointegration test

When cross-sectional dependence (CSD) is present, standard panel stationarity approaches such as the ADF test become futile. Therefore, this issue can be addressed by modifying the classic ADF method, incorporating cross-sectional mean adjustments of lagged terms, and restructuring one of the component structures, resulting in a novel panel unit root assessment that accommodates both CSD and heterogeneity. CIPS stationarity test is based on the average of individual CADF tests [59]. This indicates that certain factors are relevant to the CIPS test.

$$CIPS\ (N,T) = \frac{1}{N}\sum_{i=1}^{N} t_i(N,T) \tag{17}$$

This study further adopts the Westerlund and Edgerton [60] method. The co-integration test is shown in the equation

$$\Delta Y_{it} = \psi_i d_i + a_i(Y_{it-1} - \beta_i X_{it-1}) + \sum_{j=1}^{p_i} a_{ij}\Delta Y_{it-j} + \sum_{j=-pi}^{p_i}\varphi_{ij}\Delta X_{i,t-j} + \mu_{it} \tag{18}$$

$d_i = (1,t)$ gives trend elasticity measure $\psi_i = \psi_i$ *and* $\psi_{2i}$ shows the constant term for the states and $i$ *and* $t$ indicates the CSD. Test statistics categories of the approach are shown in equations (19)–(21):

$$G_t = \sum_{i=1}^{N}\frac{n_i}{S.E(\eta_i}^{\frac{1}{4}} \tag{19}$$

$$G_a = \frac{1}{N}\sum_{i=2}^{N}\frac{T\eta_i}{1 - \sum_{j=1}^{k}\eta_{ij}} \tag{20}$$

The cointegration statistics is expressed mathematically as:

$$P_\tau = \frac{\eta_i}{S.E\ (\eta_i)} \tag{21}$$

$$P_a = T\eta_i$$

$G_\tau$ *and* $G_a$ shows the group mean figures, $P_\tau$ *and* $P_a$ also indicates the statistics in panel, $\eta_i$ shows the transition from short to long-term equilibrium speed.

### 3.3.3. Parameters estimation

We utilise regression with Reg-DK and the MMQReg for two-panel estimation techniques. These techniques are assumptions-made and address estimation problems that may not make parameter estimates valid. The Reg-DK is heteroscedastic and robust for general forms of CSD in deriving slope coefficients [23]. In terms of the way by which the error term $\varepsilon_{i,t}$ is treated, Reg-DK estimates three different models: the pooled (constant effect) model (POL-DK), the fixed effects model (FE-DK), and the random effects GLS model (RE-DK), which treats the error term as a random variable. The most appropriate and efficient Reg-DK model is selected using the Hausman test. This way, MMQReg is expected to extend the policy implications by accounting for distributional heterogeneity. The MMQReg model in Machado and Silva [61] would bring heterogeneous and distributional effects across quantile locations of the dependent variable. For a location-scale model, the conditional quantile $Q_y\left(\frac{\tau}{X_{it}}\right)$ is defined by:

$$Q_y\left(\frac{\tau}{X_{it}}\right) = a_i + \delta_i q_i(\tau) + X_{it}^{\prime}\varphi + Z_{it}^{\prime}\gamma q(\tau) \tag{22}$$

where $X_{it}$ is a vector of regressors, and $a_i + \delta_i q_i(\tau)$ It is the scalar coefficient of the quantile-$\tau$ fixed effect at $\tau$ that are time-invariant parameters, the heterogeneous effects of which are allowed to vary across the quantiles of Y. We can model how the functional relationship in Eq. (4) manifests in across quantiles as follows:

$$QlnEI_{i,t}\left[\tau / a_i, \varepsilon_{it}, X_{i,t}\right] = \varphi_{i0} + \varphi_{1a\tau} lnPgdp_{1i,t} + \varphi_{2a\tau}\ ln\ PgdpSQ_{i,t} + \varphi_{3a\tau} lnRE_{i,t} + \varphi_{ma\tau} lnMrk_{i,t} + \varphi_{mqa\tau} lnMrk_{i,t} + \varepsilon_{i,t} \tag{23}$$

where, $QlnEI_{i,t}[\tau/a_{i},\varepsilon_{it},X_{i,t}]$ is the quantile of lnEI with the scalar coefficient $(a_i(\tau))$ for the distributional effect at $\tau$. By setting $\tau$ between 0 and 1, such as 0.2, we obtain the 20th quantile equation for the distribution of LNEI.

## 4. Results and discussion

### 4.1. Model validation tests

The results from Tables 3–7 provide robust econometric evidence supporting the validity and stability of the models. The Hausman test in Table 3 strongly rejects the null hypothesis, indicating that the fixed effects model is the appropriate specification. Table 4 shows that multicollinearity is not a concern, as the variance inflation factor (VIF) values remain well below the critical threshold of 10. The results in Table 5 suggest the presence of cross-sectional dependence in most variables, except for financial freedom, emphasising the need for second-generation unit root tests. Table 6 confirms that all variables are non-stationary at levels but become stationary after first differencing, supporting their integration of order one, I(1). Finally, Table 7 establishes long-run relationships among the variables through the Westerlund and Edgerton [60] panel cointegration test, where the rejection of the null hypothesis in most cases indicates robust cointegration. These findings confirm the econometric approach's appropriateness and the estimated relationships' validity.

### 4.2. Mean effect analysis

The mean effects, relying on the Driscoll-Kraay adjusted fixed effects model, are given in Table 8. The coefficient on lnPgdp is positive and highly significant across all model specifications, ranging from 1.927 to 2.045, indicating that economic growth increases energy intensity, contrary to the observation that GDP usually bears some negative effect on energy intensity, implying that with the increase in income level, energy efficiency is gained by the economy [33]. This result aligns with the early-stage industrialisation argument, where economic expansion leads to increased energy consumption due to industrial demand and urbanisation [35]. However, the squared term lnPgdpSQ is negative and significant, ranging from −0.115 to −0.123, confirming an inverted-U-shaped relationship between economic growth and energy intensity, consistent with the EKC hypothesis. This observation aligns with Kepplinger et al. [29], who, using mixed-effect models to examine the causes of EI in the manufacturing industry in both OECD and non-OECD nations, found that GDP is adversely correlated with EI. This suggests that while energy intensity initially rises with economic development, it declines as economies transition towards service-based industries and adopt energy-efficient technologies. Governments should support industrial modernisation and energy efficiency initiatives at higher income levels to accelerate the transition to a low-energy-intensive economy.

The coefficient for lnRE is negative and statistically significant across all specifications, ranging from −0.325 to −0.352. This implies that a 1 % increase in renewable energy consumption leads to a reduction in energy intensity by approximately 0.325 %–0.352 %, demonstrating the vital role of renewables in enhancing energy efficiency. This aligns with prior works, where RE usage is acknowledged as significantly influencing the atmosphere by reducing $CO_2$ emissions [37,38]. The observed reduction in energy intensity due to renewable energy consumption suggests that countries investing in renewables can achieve dual benefits of environmental sustainability and energy efficiency, as seen in China [39]. This effect is particularly significant, as a shift from traditional biomass and inefficient energy systems towards modern renewable sources such as solar, wind, and hydropower can potentially drive long-term reductions in energy intensity. African economies must prioritise renewable energy investments, develop incentives to encourage private-sector participation, and integrate renewables into national energy grids to maximise their efficiency-enhancing benefits.

**Table 3**
Results from Hausman test.

| Model Specification | chi2(6) | Prob > chi2 |
|---|---|---|
| *ln*EI = *f*(*ln*Pgdp, *ln*PgdpSQ, *ln*RE, *ln*FinF) | 30.310[a] | 0.000 |
| *ln*EI = *f*(*ln*Pgdp, *ln*PgdpSQ, *ln*RE, *ln*INVF) | 32.410[a] | 0.000 |
| *ln*EI = *f*(*ln*Pgdp, *ln*PgdpSQ, *ln*RE, *ln*TRDF) | 21.720[a] | 0.000 |
| *ln*EI = *f*(*ln*Pgdp, *ln*PgdpSQ, *ln*RE, *ln*FinF, *ln*INVF, *ln*TRDF) | 36.780[a] | 0.000 |
| *ln*EI = *f*(*ln*Pgdp, *ln*PgdpSQ, *ln*RE, *ln*MrkF) | 28.880[a] | 0.000 |
| *ln*EI = *f*(*ln*Pgdp, *ln*PgdpSQ, *ln*RE, *ln*MrkF, *ln*MrkFSQ) | 37.310[a] | 0.000 |

[a] $p < 0.01$.

**Table 4**
Variance inflation factors (VIF) tests.

| Tests | (1) | | (2) | |
|---|---|---|---|---|
| | VIF | 1/VIF | VIF | 1/VIF |
| *ln*Pgdp (*ln*PgdpSQ) | 2.12 | 0.472 | 2.11 | 0.474 |
| *ln*RE | 2.12 | 0.472 | 2.08 | 0.479 |
| *ln*MrkF (*ln*MrkFSQ) | | | 1.05 | 0.951 |
| *ln*FinF | 1.68 | 0.596 | | |
| *ln*INVF | 1.62 | 0.618 | | |
| *ln*TRDF | 1.08 | 0.926 | | |
| **Mean VIF** | 1.72 | | 1.75 | |

Theoretical benchmark: VIF = 10; Mean VIF = 6.

**Table 5**
Pesaran [59] cross-section dependence test.

| Variable | CD-test | p-value | average joint | mean ρ | mean abs(ρ) |
|---|---|---|---|---|---|
| *ln*EI | 16.347*** | 0.000 | 24.00 | 0.14 | 0.36 |
| *ln*Pgdp | 59.885*** | 0.000 | 24.00 | 0.52 | 0.65 |
| *ln*PgdpSQ | 59.757*** | 0.000 | 24.00 | 0.51 | 0.64 |
| *ln*RE | 51.137*** | 0.000 | 24.00 | 0.44 | 0.60 |
| *ln*MrkF | 17.159*** | 0.000 | 24.00 | 0.15 | 0.36 |
| *ln*MrkFSQ | 17.357*** | 0.000 | 24.00 | 0.15 | 0.36 |
| *ln*FinF | 1.119 | 0.263 | 24.00 | 0.01 | 0.35 |
| *ln*INVF | 16.674*** | 0.000 | 24.00 | 0.15 | 0.38 |
| *ln*TRDF | 45.009*** | 0.000 | 24.00 | 0.39 | 0.43 |

Note:, CD ~ N(0,1); ***$p < 0.01$.

**Table 6**
Panel unit root tests.

| Variables | Level I(0) | | 1st Difference I(1) | | Results |
|---|---|---|---|---|---|
| | Constant | Constant and Trend | Constant | Constant and Trend | |
| **Panel A: Pesaran's CADF test** | | | | | |
| lnEI | −1.566 | −1.821 | −4.526*** | −4.63*** | I(1) |
| lnPCgdp | −1.477 | −1.554 | −3.278*** | −3.715*** | I(1) |
| lnPCgdpSQ | −1.424 | −1.481 | −3.264*** | −3.676*** | I(1) |
| lnMrkF | −1.553 | −1.884 | −4.317*** | −4.476*** | I(1) |
| lnMrkFSQ | −1.563 | −1.891 | −4.332*** | −4.486*** | I(1) |
| lnRE | −1.493 | −1.791 | −4.286*** | −4.393*** | I(1) |
| lnFinFrd | −1.849 | −2.117 | −4.461*** | −4.674*** | I(1) |
| lnINVFrd | −1.534 | −2.089 | −3.905*** | −3.934*** | I(1) |
| lnTRDFrd | −1.313 | −1.311 | −4.98*** | −5.119*** | I(1) |
| **Panel B: CIPS** | | | | | |
| lnEI | −1.597 | −0.999 | −4.526*** | −4.630*** | I(1) |
| lnPCgdp | −1.314 | −1.172 | −3.278*** | −3.715*** | I(1) |
| lnPCgdpSQ | −1.237 | −1.059 | −3.264*** | −3.676*** | I(1) |
| lnRE | −1.868 | −2.464 | −4.286*** | −4.393*** | I(1) |
| lnMrkF | −1.466 | −1.984 | −3.173*** | −3.881*** | I(1) |
| lnMrkFSQ | −1.494 | −2.092 | −3.143*** | −3.821*** | I(1) |
| lnFinFrd | −1.751 | −2.274 | −4.461*** | −4.674*** | I(1) |
| lnINVFrd | −1.534 | −2.089 | −3.261*** | −3.301*** | I(1) |
| lnTRDFrd | −1.313 | −1.311 | −3.641*** | −3.703*** | I(1) |

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

**Table 7**
Westerlund [60] ECM panel cointegration test.

| Stats | (1) FinF | (2) INVF | (3) TRDF | (4) Combined | (5) MrkF | (6) Quadratic term |
|---|---|---|---|---|---|---|
| Gt | −3.048*** | −3.308*** | −3.232*** | −2.732** | −3.157*** | −2.946** |
| (RP-Val) | (0.000) | (0.000) | (0.000) | (0.020) | (0.000) | (0.020) |
| Ga | −11.603*** | −12.443*** | −11.695*** | −8.263*** | −11.435*** | −9.568*** |
| (RP-Val) | (0.000) | (0.000) | (0.000) | (0.020) | (0.000) | (0.010) |
| Pt | −22.111*** | −21.436*** | −25.940*** | −14.994* | −23.042*** | −20.544*** |
| (RP-Val) | (0.000) | (0.000) | (0.000) | (0.080) | (0.000) | (0.000) |
| Pa | −10.823*** | −10.567*** | −12.602*** | −8.176** | −11.930*** | −9.575*** |
| (RP-Val) | (0.000) | (0.000) | (0.000) | (0.020) | (0.000) | (0.010) |

Robust P-Val from 100 bootstrap replications; ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

**Table 8**
Mean effect analysis using FE-regression.

| Variables | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| *ln*Pgdp | 2.020*** | 1.927*** | 2.045*** | 1.945*** | 2.007*** | 2.007*** |
| | (0.110) | (0.098) | (0.092) | (0.101) | (0.101) | (0.106) |
| | [18.442] | [19.708] | [22.318] | [19.265] | [19.893] | [18.910] |
| *ln*PgdpSQ | −0.120*** | −0.115*** | −0.123*** | −0.115*** | −0.119*** | −0.120*** |
| | (0.008) | (0.007) | (0.006) | (0.007) | (0.007) | (0.007) |
| | [-15.290] | [-16.680] | [-19.124] | [-15.902] | [-16.650] | [-16.060] |
| *ln*RE | −0.336*** | −0.352*** | −0.325*** | −0.351*** | −0.345*** | −0.347*** |
| | (0.012) | (0.015) | (0.013) | (0.015) | (0.014) | (0.014) |
| | [-27.023] | [-22.748] | [-24.563] | [-23.496] | [-25.081] | [-25.122] |
| *ln*FinF | −0.305*** | | | −0.147** | | |
| | (0.053) | | | (0.060) | | |
| | [-5.760] | | | [-2.464] | | |
| *ln*INVF | | −0.301*** | | −0.222*** | | |
| | | (0.032) | | (0.033) | | |
| | | [-9.493] | | [-6.746] | | |
| *ln*TRDF | | | −0.089** | −0.001 | | |
| | | | (0.036) | (0.042) | | |
| | | | [-2.443] | [-0.029] | | |
| *ln*MrkF | | | | | −0.519*** | 3.888** |
| | | | | | (0.075) | (1.525) |
| | | | | | [-6.946] | [2.549] |
| *ln*MrkFSQ | | | | | | −16.463** |
| | | | | | | (5.867) |
| | | | | | | [-2.806] |
| Constant | −5.197*** | −4.704*** | −6.040*** | −4.557*** | −4.181*** | 1.063 |
| | (0.505) | (0.380) | (0.420) | (0.479) | (0.575) | (2.054) |
| | [-10.294] | [-12.389] | [-14.397] | [-9.518] | [-7.266] | [0.517] |
| Observations | 816 | 816 | 816 | 816 | 816 | 816 |
| R-squared | 0.528 | 0.540 | 0.491 | 0.546 | 0.526 | 0.538 |
| Number of groups | 34 | 34 | 34 | 34 | 34 | 34 |

Driscoll-Kraay standard errors in brackets; ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

Additionally, energy storage technologies and smart grid infrastructure improvements will ensure a stable and sustainable supply of renewable energy, amplifying its impact on reducing energy intensity.

The results for the disaggregated open market indicators reveal important insights into how market liberalisation affects energy intensity. Financial freedom, represented by lnFinF, has a significant negative effect on energy intensity, with coefficients ranging from −0.147 to −0.305, indicating that greater financial liberalisation promotes efficient capital allocation towards energy-efficient technologies and projects. However, the effect weakens in some specifications, suggesting that financial liberalisation alone may not drive substantial energy efficiency improvements [6,44]. Strengthening financial institutions and ensuring access to green finance mechanisms can enhance the role of financial freedom in energy efficiency. Investment freedom, represented by lnINVF, also has a consistently negative and significant impact on energy intensity, with coefficients between −0.222 and −0.301, highlighting the role of foreign and domestic investments in fostering energy-efficient industrialisation. Conversely, Indonesia affects energy intensity positively, thus prompting the assumption that more financial investments could lead to higher energy consumption [36]. Countries should create an investment-friendly environment, ensuring regulatory frameworks facilitate green investments and attract sustainable energy projects. Trade freedom, represented by lnTRDF, has a weaker and less consistent effect, with coefficients ranging from −0.089 to −0.001, suggesting that trade openness alone does not significantly drive energy efficiency unless complemented by policies encouraging imports of cleaner technologies, thus aligning with Gyamfi et al. [33]. Trade liberalisation policies should be aligned with environmental objectives by reducing tariffs on energy-efficient equipment and technologies.

The coefficient of lnMrkF in column (5) is negative and highly significant at −0.519, indicating that higher market freedom reduces energy intensity. This suggests economies benefit from efficiency gains, improved resource allocation, and better access to energy-saving technologies as market conditions become more liberalised. This outcome is supported by the observation that three internal Chinese economic elements (technology advancement, economic structure and energy usage framework) impact EI. In contrast, clean energy usage reduces EI [42]. A well-functioning market environment fosters competition, encourages investment in energy-efficient infrastructure, and supports innovation in sustainable energy practices. Policymakers should maintain a conducive business environment that allows firms and industries to integrate energy-efficient technologies while ensuring regulatory measures that facilitate rather than hinder market operations. In column (6), including the squared term lnMrkFSQ reveals a nonlinear relationship between market freedom and energy intensity. The coefficient for lnMrkF remains positive and significant at 3.888, while the coefficient for lnMrkFSQ is negative and statistically significant at −16.463.

This indicates an inverted U-shaped relationship between market freedom and energy intensity, implying that further liberalisation increases energy intensity at lower levels of market freedom [6,44]. However, beyond a certain threshold, market liberalisation leads to efficiency gains that reduce energy intensity. This pattern suggests that moderate market liberalisation fosters industrial growth and energy use, but, once a critical point is reached, enhanced competition and technological diffusion contribute to energy efficiency improvements. Policymakers should adopt a balanced approach, ensuring that market liberalisation is accompanied by regulatory frameworks that prevent potential inefficiencies associated with excessive deregulation. Managing the transition effectively can help maximise the benefits of market openness while mitigating unintended negative externalities on energy use and environmental sustainability.

### 4.3. *Quantile analysis*

The results in Table 9 present the distributional effects of the explanatory variables on energy intensity (EI) using the method of moments quantile regression. The varying coefficients across quantiles indicate that the impact of economic growth, renewable energy consumption, and market freedom is not uniform across different energy intensity levels. This heterogeneity suggests that policy interventions must be tailored according to the specific energy profiles of economies [62].

The coefficient of lnPgdp is positive and statistically significant across all quantiles, suggesting that economic growth generally increases energy intensity (Fig. 1). However, the magnitude of the effect rises as we move from lower to higher quantiles, indicating that economies with higher energy intensity experience a stronger link between GDP growth and energy consumption per unit of output. This implies that growth in energy-intensive economies relies more on energy use, possibly due to industrial structures that favour energy-intensive production. On the contrary, GDP usually negatively affects energy intensity, implying that with the increase in income level, energy efficiency is gained by the economy [33]. The squared term, lnPgdpSQ, is negative and significant across all quantiles, confirming an inverted U-shaped relationship between economic growth and energy intensity; this aligns with studies in ASEAN countries and the European Union, where high-income levels mean low energy intensity [34]. The more substantial negative effect at higher quantiles implies that the transition to energy efficiency occurs more prominently in economies with high energy intensity as income levels rise [11].

Renewable energy consumption (lnRE) exerts a consistently negative and significant effect on energy intensity across all quantiles, confirming that an increasing share of renewable energy in total energy consumption leads to lower energy intensity. The magnitude of this effect strengthens as we move from the lower to higher quantiles, suggesting that economies with higher energy intensity benefit more from a transition towards renewable energy. This outcome aligns with the findings obtained utilising panel data from 30 Chinese provinces spanning 2000 to 2018, and it is discovered that RE development considerably helps to lower EI in China [39,40], and is supported by Yu et al.'s (2022) observation in 82 nations using a dynamic panel threshold valuation procedure. This finding supports the argument that large-scale renewable energy integration is particularly effective in economies that currently depend heavily on fossil fuels or inefficient energy systems. It also highlights the role of technological improvements and policy

**Table 9**
Distributional effects.

| Variables | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | location | scale | qtile_10 | qtile_20 | qtile_30 | qtile_40 | qtile_50 | qtile_60 | qtile_70 | qtile_80 | qtile_90 |
| *ln*Pgdp | 2.082*** | 0.178 | 1.834*** | 1.918*** | 1.974*** | 2.022*** | 2.080*** | 2.136*** | 2.183*** | 2.270*** | 2.349*** |
| | (0.279) | (0.186) | (0.403) | (0.344) | (0.313) | (0.293) | (0.279) | (0.277) | (0.286) | (0.320) | (0.369) |
| | [7.468] | [0.960] | [4.549] | [5.578] | [6.312] | [6.899] | [7.452] | [7.700] | [7.643] | [7.091] | [6.373] |
| *ln*PgdpSQ | −0.125*** | −0.014 | −0.106*** | −0.112*** | −0.117*** | −0.121*** | −0.125*** | −0.130*** | −0.133*** | −0.140*** | −0.146*** |
| | (0.018) | (0.012) | (0.027) | (0.023) | (0.021) | (0.019) | (0.019) | (0.018) | (0.019) | (0.021) | (0.024) |
| | [-6.772] | [-1.132] | [-3.957] | [-4.930] | [-5.632] | [-6.201] | [-6.756] | [-7.037] | [-7.027] | [-6.591] | [-5.976] |
| *ln*RE | −0.348*** | −0.040** | −0.292*** | −0.311*** | −0.324*** | −0.334*** | −0.347*** | −0.360*** | −0.371*** | −0.391*** | −0.408*** |
| | (0.026) | (0.017) | (0.038) | (0.032) | (0.029) | (0.027) | (0.026) | (0.026) | (0.027) | (0.030) | (0.034) |
| | [-13.412] | [-2.337] | [-7.739] | [-9.734] | [-11.149] | [-12.270] | [-13.374] | [-13.960] | [-13.931] | [-13.108] | [-11.895] |
| *ln*MrkF | 4.124*** | −0.422 | 4.710** | 4.510** | 4.377** | 4.265*** | 4.129*** | 3.994*** | 3.883** | 3.679** | 3.492* |
| | (1.515) | (1.010) | (2.189) | (1.870) | (1.701) | (1.593) | (1.516) | (1.508) | (1.552) | (1.739) | (2.002) |
| | [2.723] | [-0.418] | [2.152] | [2.412] | [2.574] | [2.678] | [2.723] | [2.649] | [2.502] | [2.115] | [1.744] |
| *ln*MrkFSQ | −17.303*** | 0.509 | −18.009** | −17.768** | −17.609*** | −17.474*** | −17.309*** | −17.147*** | −17.013*** | −16.767** | −16.542** |
| | (5.795) | (3.865) | (8.373) | (7.154) | (6.507) | (6.094) | (5.801) | (5.769) | (5.937) | (6.654) | (7.661) |
| | [-2.986] | [0.132] | [-2.151] | [-2.484] | [-2.706] | [-2.867] | [-2.984] | [-2.972] | [-2.865] | [-2.520] | [-2.159] |
| Constant | 1.007 | 0.868 | −0.198 | 0.214 | 0.486 | 0.716 | 0.997 | 1.274 | 1.502 | 1.922 | 2.306 |
| | (2.186) | (1.458) | (3.160) | (2.697) | (2.452) | (2.298) | (2.188) | (2.175) | (2.240) | (2.509) | (2.889) |
| | [0.461] | [0.596] | [-0.063] | [0.079] | [0.198] | [0.312] | [0.456] | [0.586] | [0.671] | [0.766] | [0.798] |
| Observations | 816 | 816 | 816 | 816 | 816 | 816 | 816 | 816 | 816 | 816 | 816 |

Standard errors in brackets; ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

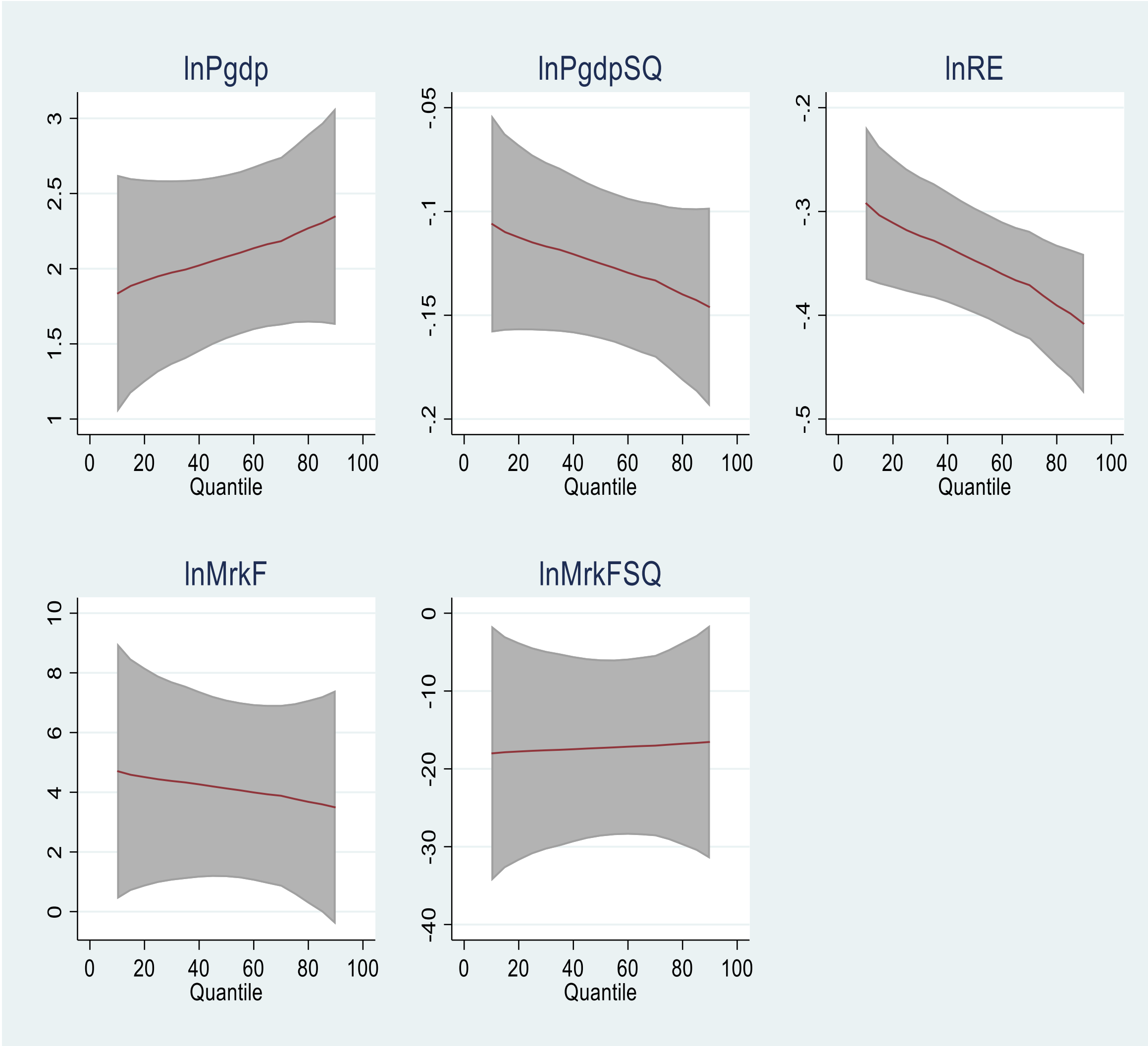


**Fig. 1.** Quantile plots.

frameworks in enhancing the efficiency gains associated with renewable energy adoption.

Open market conditions (lnMrkF) positively and significantly affect energy intensity at most quantiles, but its impact weakens at higher quantiles. This suggests that greater market freedom initially promotes economic activity that is energy-intensive, possibly due to increased industrialisation and economic liberalisation leading to higher energy demand. However, as energy intensity increases, the effect of the open market system becomes less pronounced, likely due to regulatory mechanisms or shifts in economic structure that encourage energy efficiency [6,45]. The squared term of market freedom (lnMrkFSQ) is negative and significant across most quantiles, reinforcing the non-linear relationship, contrary to the observation in Indonesia where energy intensity is positive, thus prompting the assumption that more open market conditions could lead to higher energy consumption [36]. This suggests that while market liberalisation initially increases energy use, it fosters efficiency improvements over time, possibly through adopting energy-saving technologies, market-driven innovation, or structural economic shifts towards less energy-intensive sectors.

The heterogeneity in coefficients across quantiles highlights that the impact of economic growth, renewable energy and market freedom varies depending on the level of energy intensity in an economy [48,49]. Economic growth is dominant in increasing energy consumption in economies with lower energy intensity, while renewable energy and market mechanisms have relatively weaker effects [25,26]. However, in economies with higher energy intensity, the mitigation effects of renewable energy and market regulation become more muscular, indicating that energy efficiency improvements and cleaner energy transitions are more critical for reducing energy intensity in these contexts.

These findings have important policy implications. Policies aimed at reducing energy intensity should be designed with an understanding that their effectiveness will vary depending on the existing energy intensity level of the economy. In economies with lower energy intensity, strategies that promote economic growth and incremental energy efficiency improvements may be sufficient. However, for economies with high energy intensity, more aggressive policy interventions such as expanding renewable energy capacity, enforcing stricter energy efficiency regulations and incentivising technological innovation will be necessary to achieve meaningful reductions in energy intensity. Furthermore, while market freedom can contribute to efficiency improvements in the long run, it should be accompanied by regulatory measures that ensure economic liberalisation does not lead to excessive energy consumption. This nuanced understanding of how policy variables interact with energy intensity across different quantiles provides a more substantial basis for designing effective energy policies that balance economic growth with sustainability objectives.

## 5. Conclusion and policy implications

### 5.1. Conclusion

The study gives insight into the relationship between economic growth, the adoption of renewable energy, and energy intensity in Africa, indicating that economic growth increases energy intensity (EI) in the initial stage. However, as the economy develops, it transitions to more energy-efficient practices. Results corroborate the environmental Kuznets curve (EKC) theory, which states that higher income levels reduce energy intensity as economies shift to service and adopt energy-efficient technologies. Renewable energy consumption (RE) is found to indeed reduce energy intensity, especially in economies with greater initial energy dependence, which reaffirms the importance of transition to renewables for sustainable development. Also highlighted in this study are the aspects of market systems and institutional conditions as enumerated by institutional theory. More independence in finance, investment and trade will improve energy efficiency, but the leverage wall depend on regulations and market systems' maturity. The records in this study show that, in the interim, more market liberalisation would generally cause higher energy consumption until, beyond some critical threshold, it drives energy efficiency improvement. Thus, it emphasises renewable energy investments, supporting market liberalisation with effective regulatory frameworks, and encouraging institutional reforms to follow with energy efficiency. An appropriate balance between economic growth, renewable energy acceptance and market freedom will help reduce energy intensity and achieve sustained sustainable development. The study helps deepen understanding of the pathways to energy-efficient growth.

### 5.2. Policy implications

Governments in Africa must prioritise investment in renewable energy to enhance energy intensity reduction and promote sustainable development. In the short term, renewable energy project financial incentives, subsidies and tax deductions will attract local and international investments. By creating an attractive financing environment for renewable energy, governments can encourage private sector participation and fast-track the shift towards cleaner energy sources. Furthermore, grid integration of renewable energy and construction of infrastructure for large-scale deployment should be prioritised. This entails upgrading old grids to allow the integration of renewable energy inputs while ensuring rural and off-grid areas also get access to renewable energy solutions.

Moreover, it is imperative to develop green finance mechanisms like green bonds and low-interest loans to provide affordable capital for renewable energy and energy efficiency projects. Inviting international financial institutions to cooperate with governments would be beneficial for mobilising investments and increasing access to climate finance. Strengthened financing institutions to enhance energy-efficient technologies will fundamentally support the transition to a low-energy future economy. This could include forming green investment funds and incentivising banks to finance renewable energy projects. Besides this, energy efficiency market regulations should also be strengthened, which may include energy efficiency standards for industry, buildings and appliances. The policies should incentivise companies to implement cleaner production with tax breaks, grants and research funding for energy-efficient innovations. Furthermore, governments must ensure a stable supply of renewable energy with the help of smart grids and energy storage systems, hence boosting grid reliability and reducing energy losses.

At the same time, these countries must encourage technological innovation through increased investments in R&D and by promoting collaboration between different sectors of the economy: academic, industrial and governmental. Besides creating innovation hubs, governments should fund research into energy technologies tailored to Africa's exceptional energy environment. It is also important that market liberalisation is accompanied by environmental policies, like reducing tariffs for energy-efficient technologies and importing cleaner energy products. Whereas the initial stage of market liberalisation might raise energy intensity, it could offer both motivation and reward for efficiency improvements as the economies reach maturity, thus rendering it imperative that reforms be implemented gradually.

Given the different energy profiles each economy possesses, it would be advisable for energy-intensive countries to emphasise the use of renewable energy and energy efficiency. In contrast, energy-non-intensive countries should look towards diversification and economically energy-efficient industrial growth. In countries with very high energy use, there is a need to hasten the promotion of large-scale renewable energy generation plants, such as wind farms and solar installations, along with energy-efficiency improvements in the industrial and commercial sectors. Ultimately, capacity-building efforts will be strengthened through training programmes for the stakeholders in the public and private sectors, ensuring a well-skilled workforce that can effectively apply energy efficiency technologies and renewable energy systems.

Choosing such a path would allow Africa to smoothly transform its economy into a low-energy-intensive, sustainable growth path that fosters long-term growth while also helping to reduce environmental impacts. Renewable energy investments, strengthening financial systems, enhancing innovation and ensuring that interventions find their most outstanding merit in targeted policy support will fast-track the African approach towards sustainable development.

### 5.3. Study limitations and suggestions for future research

The study is conducted at the national level, which does not consider the heterogeneity in

Energy intensity within industry, transportation and residential energy use. This sectoral heterogeneity could give another view of the basis of efficiency. Future research should, where possible, be sector-specific, determining which drivers of energy intensity are most specific to different economic activities. Understanding these shades can help policymakers design targeted interventions. Another direction could be the role of emerging technologies like smart grids, complete digitalisation, and artificial intelligence in reducing energy intensity. These innovations hold immense potential for transforming energy systems and improving efficiency. Cross-regional comparisons between African nations and other developing regions could be informative concerning best practices and successful policy models. Future studies can consider same or similar theme for other regions like European union, China among others.

## CRediT authorship contribution statement

**Festus Victor Bekun:** Writing – original draft, Conceptualization. **Michael Provide Fumey:** Formal analysis, Data curation. **Marcin W. Staniewski:** Writing – review & editing, Writing – original draft. **Lipeng Sun:** Methodology, Formal analysis. **Philips O. Agboola:** Writing – review & editing, Supervision.

## 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.

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## Appendix

**Table A1**
List of countries investigated

| List of Countries: |
|---|
| Benin; Botswana; Burkina Faso; Cameroon; Côte d'Ivoire; Chad; Egypt; Equatorial Guinea; Ethiopia; Gabon; Ghana; Guinea; Guinea-Bissau; Kenya; Lesotho; Madagascar; Malawi; Mali; Mauritius; Morocco; Namibia; Niger; Nigeria; Republic of Congo; Rwanda; Senegal; South Africa; Tanzania; The Gambia; Togo; Tunisia; Uganda; Zambia; Zimbabwe |

## Data availability

Data will be made available on request.

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