



How energy transition and fintech influence income inequality in Sub-Saharan Africa: Evidence from a panel-corrected standard error approach



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ABSTRACT

This study explores the role of financial technology (FinTech) and the energy transition in shaping income inequality across 45 sub-Saharan African economies (SSA). By employing the panel-corrected standard errors approach, the analysis takes into account contextual and institutional factors, as well as regional specificities, for the period extending from 2000 to 2021. This research elucidates the connections among energy transition, FinTech, and income inequality, emphasizing their significance for economic progress and clean energy access. The findings reveal significant inequality in the outcomes of SSA countries, with an average Gini index of 43.197, indicating that most countries are unequal. This study reveals a notable connection between transitioning to renewable energy sources and a reduction in income inequality, with a one-unit increase in the energy transition indicator resulting in a 5.10% decrease in inequality. Moreover, FinTech is also found to contribute to a reduction in income inequality, with a 1.31% decrease observed for every unit increase in the FinTech indicator. The analysis also revealed a weak, yet statistically significant, link between population density and income inequality, with a one-unit increase in inequality of 0.00632%. Notably, industrial value added is found to be an influential factor with a statistically significant coefficient of 0.129. The key implications of the study emphasize the importance of redistributive policies, financial inclusion, and the promotion of renewable energy sources in constructing more inclusive economic systems. Furthermore, the study underscores the significant value of accurate energy production prediction for informed decision-making in energy planning and policy-making on regional and global scales.

1. Introduction

The energy transition represents a foundational transformation of the energy system away from fossil fuels toward renewable energy sources, propelled by the necessity of addressing climate change [1]. The implementation and utilization of renewable energy technologies, including solar, wind, and hydroelectric power, serve as essential drivers of the energy transition [2]. In response, numerous countries worldwide are adopting renewable energy to alleviate carbon emissions while fostering economic growth opportunities. However, the role of the energy transition in fostering inclusive economic growth and reducing income inequality remains inadequately investigated.

The growing adoption of financial technology (FinTech) represents another critical issue that has reshaped the financial industry. FinTech

has the potential to facilitate access to financing for individuals and businesses, particularly in low-income countries, which have historically struggled to secure formal financial services [3]. The factors associated with FinTech have the potential to create jobs, reduce economic inequality, and enhance the provision of financial services. However, the impact of FinTech on income distribution has not been fully explored in the context of developing countries, especially in sub-Saharan Africa (SSA), as this potential depends on whether the adoption of FinTech fosters an inclusive economy [4].

SSAs home to approximately 1.1 billion people. It is characterized by an energy mix heavily reliant on fossil fuels, inadequate energy infrastructure, and limited access to modern energy services. Energy poverty rates (the percentage of the population without access to electricity and clean cooking facilities) are among the highest globally,

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with only a tiny fraction of the region's population having access to modern energy services. At the same time, the region is heavily reliant on agriculture, which employs a significant proportion of the labor force. Income inequality and poverty are pervasive, with rural households continuing to bear the brunt of poverty. Energy transition and FinTech have the potential to address energy poverty, create jobs, and enhance financial inclusion, although their relationships with income inequality are uncertain [5].

Given the significant challenges of energy poverty and income inequality in Sub-Saharan Africa, it is essential to examine the relationships among energy transition, FinTech, and income distribution. This study is significant because it seeks to identify strategies that policymakers can use to ensure that energy transition and FinTech contribute to inclusive growth and reduce income inequality. Understanding the impact of these factors is essential for achieving Sustainable Development Goal 10 — to reduce inequality — and other goals. This research provides insights that inform policy decisions about the role of renewable energy sources and financial technology in creating an inclusive and sustainable economy, particularly in SSA.

The rapid pace of energy transition and FinTech adoption presents both opportunities and challenges for SSA economies. Although renewable energy has the potential to lower energy poverty and reduce greenhouse gas emissions, its long-term impact on income inequality remains uncertain. Similarly, while FinTech offers opportunities to enhance financial inclusion and create jobs, it can also create new forms of inequality. Consequently, focusing on the extent to which renewable energy and FinTech contribute to reducing income inequality in SSA is essential.

In this article, we emphasize the unique and innovative contributions of our research to the literature, focusing on SSA, where energy poverty and income inequality remain pervasive issues [5]. Based on [6–11], our study aims to differentiate itself by examining the combined impact of energy transition and financial technology on income inequality, as opposed to prior research focusing on individual effects. We aim to contribute to the literature by exploring three main aspects: interconnected areas, contextual factors, and empirical analysis. Our research provides a more comprehensive understanding of the intricate relationships among energy transition, financial technology, and income inequality in the context of sub-Saharan Africa. By highlighting the significance of examining contextual, institutional, and regional factors, this research aims to offer tailored strategies to address the impact of energy transition and financial technology on income inequality in the region. Furthermore, we conduct empirical analysis using Driscoll and Kraay's panel corrected standard error technique, accounting for panel data issues such as cross-sectional dependency, autocorrelation, and heteroskedasticity.

These aspects highlight the study's added value compared to previous research, which mostly examined the individual effects of renewable energy sources and financial technology [12–23]. By exploring their combined effects, we promote a better understanding of the complex relationships among energy transition, FinTech, and income distribution. Furthermore, we address a scarcity of research on income inequality in Sub-Saharan Africa, contributing to knowledge that can inform policy makers about economic decisions for the benefit of an equitable and sustainable economic future.

Although this study explores the possible synergies between energy transition and FinTech in reducing income inequality in sub-Saharan Africa, we argue that by considering these two key domains of innovation, there could be potential opportunities for promoting a just and equitable transition toward more sustainable energy systems [18]. Additionally, the research emphasizes the importance of examining institutional and contextual factors that influence the impact of energy transition and FinTech on inequality. By considering these aspects, we can better understand the regional specifics of sub-Saharan Africa and assess the potential synergies between energy transition and FinTech [13,15,18]. Furthermore, this study provides a more comprehensive

examination of the combined impact of energy transition and FinTech on income inequality, enabling policymakers to maximize their potential and promote an equitable transition toward more sustainable energy systems [13].

This study investigates the connection between FinTech and the energy transition on income inequality across 45 SSA economies using data from 2000 to 2021. This research employs the panel-corrected standard errors approach to account for contextual and institutional factors, as well as regional specificities. The findings show an average Gini index of 43.197, with a one-unit increase in the energy transition and FinTech indicators resulting in a 5.10% and 1.31% reduction in income inequality, respectively. Population density has a weak, statistically significant impact, while industrial value added is found to be influential, with a coefficient of 0.129.

The remainder of this paper is structured as follows: [Section 2](#) provides a review of the literature on energy transition, FinTech, and income inequality, discussing key concepts and theories. [Section 3](#) outlines the methodology used for this study, including the data sources and statistical analysis. [Section 4](#) presents the main findings of the empirical analysis. [Section 5](#) concludes with a discussion of the implications of these findings for policymakers, the limitations of the study and future research directions.

2. Literature review

2.1. Energy transition and inequality

Energy transition is a crucial path toward achieving a sustainable future, and its implications for inequality have been identified as a key concern [12,14,21,24–29]. Previous studies have investigated various aspects of the relationship between energy transition and inequality. For instance, Tang et al. [30] reveal that government spending reduces income inequality across all quantiles, highlighting the importance of government policies in shaping the relationships among energy transition, FinTech, and income inequality. Wu et al. [31] demonstrated that informational and cultural globalization, research and development, and urban concentration impact income inequality differently, offering valuable insights into how various factors influence income inequality in sub-Saharan Africa.

Several studies highlight the relationship between energy transition and income inequality, offering a diverse perspective on the topic. First, Li et al. [7] discovered a nonlinear relationship between energy efficiency and urbanization with carbon emissions in the transport sector of 30 Chinese provinces. Their research revealed that improving energy efficiency led to a stronger inhibitory effect on carbon emissions, while urbanization, though lowering emissions, had less impact. Wang et al. [11] confirmed the environmental Kuznets curve (EKC) hypothesis by observing the diverse effects of renewable energy consumption and human capital on carbon emissions before and after the EKC turning point. Their findings showed that trade openness reduced carbon emissions in countries with weak decoupling after the EKC turning point, but natural resource rents tended to increase emissions in most countries.

In addition to these findings, Wang et al. [9] revealed a heterogeneous and asymmetric influence of trade openness on carbon emissions—it increases emissions at specific quantile levels but decreases them at others. Moreover, trade diversification has been found to contribute to the reduction of emissions. Furthermore, studies on renewable energy, such as that of Wang et al. [8], reveal that AI promotes energy transition and carbon emission reduction, with trade openness playing a mediating role. However, the impact of artificial intelligence (AI) on carbon emissions is influenced by a single threshold of trade openness and a double threshold of trade openness in the impact of AI on energy transition. By understanding the nuances of these studies, we can better comprehend the intricate relationship between energy transition and income inequality and build informed policies for

addressing this critical concern.

2.2. Fintech and inequality

The rise of FinTech has transformed how people store, save, borrow, transfer, and invest money, with significant implications for income inequality [13,16,17,32]. Several studies have examined the impact of FinTech on financial inclusion, gender inequality, and income inequality. For instance, Ashenafi and Dong [13] investigated the impact of financial inclusion and FinTech on income inequality in 39 African countries and found that while FinTech promotes financial inclusion, it also exacerbates income inequality. On the other hand, Loko and Yang [32] analyze a dataset of 114 economies from around the world and find that the adoption of FinTech has significantly improved the employment of women and reduced gender inequality. Similarly, Chinoda and Mashamba [33] examine the interaction between financial technology, financial inclusion and income inequality in 25 African countries and find that financial inclusion mediates the relationship between financial technology and income inequality and plays a fundamental role in reducing income inequality in Africa.

Other studies have also examined the mechanisms through which FinTech impacts income inequality. For instance, Demir et al. [16] utilize panel data for 140 countries and discover that financial inclusion is a significant channel through which FinTech decreases income inequality, with the majority of impacts observed in higher-income countries. Odei-Appiah et al. [34] investigated the influence of FinTech usage on financial inclusion using survey data from 282 participants. By detecting a positive impact of FinTech adoption on financial inclusion, they also find that digital divide measures moderate this correlation.

Furthermore, in the more general setting, the perspective emphasizes the importance of balancing economic development, renewable energy, and ecological footprints to achieve carbon neutrality and reduce income inequality. In the study by Li et al. [6], increased geopolitical risk and energy intensity were found to correlate with heightened carbon emissions. However, corruption governance and natural resource rents have a mitigating effect, while natural resource rents initially decrease and then increase the connection between economic growth and carbon emissions. Wang et al. [10] further explored the nonlinear impact of ICT on carbon emissions, with trade openness and financial development as threshold variables. The study reveals that ICT has varying impacts on carbon emissions, depending on income levels, trade openness, and financial development.

Other studies have focused on specific regions or countries. Moghadam and Karami [34] analyze the impact of financial inclusion through fintech on women's financial empowerment in 113 countries and find a positive and significant relationship in countries classified by low levels of gender discrimination. Saraswati et al. [35] conducted a study using a partial adjustment model and data from 1990 to 2017 to investigate the effects of FinTech 3.0 development in Indonesia. Their results suggest that the development of FinTech 3.0 has a significant impact on income inequality in Indonesia.

In addition, studies have examined the legal and regulatory issues surrounding FinTech and inequality. Rambaud and Gázquez [36] show that legal regimes for FinTech, or regulatory technology, must be established to transform new technologies into ordinary instruments of the financial system, with particular attention given to the protection of personal data. Overall, the literature suggests that while FinTech has the potential to increase financial inclusion and reduce gender inequality, its impact on income inequality is complex and depends on various institutional and contextual factors. They suggest that policy-makers consider trade-offs between greater inclusion and the potential for increased income inequality and recommend taking measures to promote pro-poor financial sector development and address barriers to financial inclusion.

2.3. The link between the energy transition, FinTech and inequality

Recent developments in the fields of energy and finance have the potential to promote energy transition and reduce inequality [13,15,21]. However, it is crucial to examine the institutional and contextual factors influencing the impact of energy transition and FinTech on inequality, taking regional specificity into account [13,15,18]. A more comprehensive understanding of the combined impact of energy transition and FinTech can help maximize their potential while minimizing any potential negative effects on inequality in sub-Saharan Africa.

This study, which focuses on Sub-Saharan Africa, makes innovative contributions to the literature on energy poverty and income inequality by investigating interconnected areas, contextual factors, and empirical analysis. Breaking new ground, it delves into renewable energy, FinTech, and income distribution synergies, placing special focus on the contextual and institutional aspects unique to Sub-Saharan Africa. Utilizing Driscoll and Kraay's empirical framework, this research performs a comprehensive examination of 45 SSA economies' data, which enhances the discussion by accounting for panel data issues such as cross-sectional dependency, autocorrelation, and heteroskedasticity.

3. Methodology and data

3.1. Model specification

With respect to previous studies, this research aims to examine the influence of financial technology and energy transition on income inequality for a sample of 45 SSA economies using other regressions, as shown in Fig. 1. Based on Xu et al. [37], the analysis estimates the following Eq. 1:

$$GINI_{it} = \beta_0 + \beta_1 ET_{it} + \beta_2 FINTECH_{it} + \beta_3 GDP_{it} + \beta_4 POP_{it} + \beta_5 EMP_{it} + \beta_6 IND_{it} + \varepsilon_{it}, \quad (1)$$

where GINI, ET, FINTECH, GDP, POP, EMP and IND represent the inequality income, energy transition, FinTech index, economic growth, population density, employers and industry value added variables,

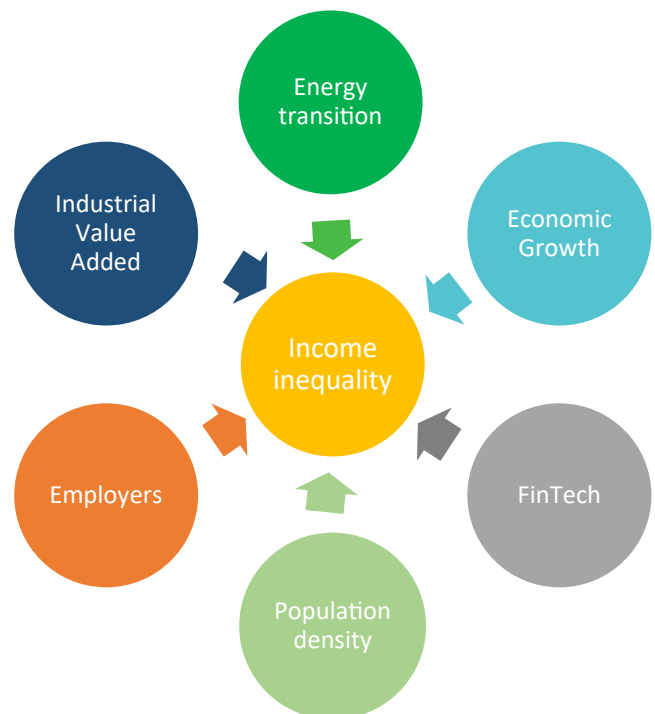


Fig. 1. Determinants of income inequality.

Table 1
Variable Description.

Variables	Symbols	Measuring Units
Income Inequality	GINI	Gini index
Energy transition	ET	Renewable energy consumption (% of total final energy consumption)
Fintech	FINTECH	indicator
Economic Growth	GDP	GDP per capita (constant 2015 US\$)
Population density	POP	Population density (people per square. km of land area)
Employers	EMP	Employers, total (% of total employment) (modeled ILO estimate)
Industrial Value Added	IND	Industry (including construction), value added (% of GDP)

respectively. The terms β_1 to β_2 show the coefficients of the attached variables, i.e., energy transition, the FinTech index, economic growth, population density, employers and industry value added, respectively. β_0 is the intercept term, and ε_{it} is the error term. Additionally, the subscript “i” indicates the cross-sectional unit (Countries), which is 45 in the current study, and the subscript “t” shows the time period ranging from 2000 to 2021. The variables ET and GDP are in logarithmic form. The interpolation method was used for data smoothing.

3.2. Econometric strategy

To estimate regression Eq. 1, first, different diagnostic tests are performed to choose a better estimation technique for the chosen data. In the first step, a cross-sectional dependency test is performed to determine the dependency in cross-sectional units. For this purpose, the Pesaran [38] CD test for cross-sectional dependence is utilized in the present study [39]. For larger cross sections (N), this test is more applicable than the Lagrange multiplier (LM) test of Breusch and Pagan [39] and is given as:

$$\text{Pesaran CD Test} = \sqrt{\frac{2T}{N(N-1)}} \left(\sum_{i=0}^{N-1} \sum_{j=i+1}^{N-1} \rho_{ij} \right). \quad (2)$$

In the second step, an autocorrelation test is conducted to explore the evidence of autocorrelation in the data. The Wooldridge serial autocorrelation test is employed in the study because it works under a lesser assumption and is thus more robust [40,41]. After the deduction of autocorrelation, as a third step, the slope heterogeneity tests of Pesaran and Yamagata [42] and Pesaran et al. [43] are utilized in the study. This test helps us determine the presence or absence of autocorrelation in unbalanced panel data, and the present study utilizes the estimator of Bersvendsen and Ditzén [44]. In the fourth step of the econometric analysis, a test for multicollinearity is applied to check for the presence of high correlations among the variables. To fulfill this objective, a variance inflation factor is calculated to detect the multicollinearity issue in panel data from 45 economies in sub-Saharan Africa.

In following all the aforementioned steps of analysis, this study employs the panel-corrected standard errors approach. It is critical to consider that panel data can suffer from cross-sectional dependency, autocorrelation, and heteroscedasticity issues. Henceforth, the integration of the panel-corrected standard errors approach in this research is of utmost importance, particularly when examining the influence of energy transition and financial technology in explaining income inequality across SSA economies. The panel data employed for this study may experience issues such as cross-sectional dependency, autocorrelation, and heteroscedasticity, which can result in biased and inefficient estimates when using conventional statistical techniques such as pooled ordinary least squares (OLS), fixed effects, and random effects. As such, adopting the panel-corrected standard errors approach is crucial for ensuring the validity and reliability of the study's findings, accounting for these potential biases in the panel data. The panel-corrected standard errors approach, popularized by Driscoll and Kraay [45], offers a means to estimate panel models in the presence of these

biases. This approach uses nonparametric estimators to calculate standard error estimates, which weigh errors by the distance between units and time, resulting in more precise estimates.

Specifically, this study utilizes the panel-corrected standard errors approach to examine the influence of financial technology and energy transition on income inequality in 45 SSA economies. Numerous studies have supported the use of this method, including [37,46,47], which have all demonstrated its effectiveness in correcting bias in panel data.

The panel-corrected standard errors approach for this study offers several advantages, including reducing bias in estimates, increasing the reliability of conclusions, and accounting for cross-sectional dependency and autocorrelation, resulting in more precise parameter estimates [48].

Thus, by choosing the panel-corrected standard errors approach, this study aims to obtain robust and precise estimates of the effects of financial technology and the energy transition on income inequality in sub-Saharan Africa, even in the presence of common issues such as heteroscedasticity, cross-sectional dependency, and autocorrelation.

3.3. Data description and source

To investigate the role of the energy transition and FinTech in explaining inequality, panel data were collected for 45 economies in sub-Saharan Africa (listed in the Appendix) from 2000 to 2021. The time period of panel data is chosen on the basis of the availability of the variables of interest in the analysis. The detailed descriptions of the variables are reported in Table 1. Inequality income is used as a dependent variable in the current analysis. To measure income inequality, the proxy variable used is the Gini index, as its usage is also evidenced in the empirical literature [49]. The data on inequality are retrieved from the World Bank [50].

However, the energy transition is used as the main independent factor. To measure energy transition, the proxy variable used is renewable energy consumption, as its usage is also evident in the empirical literature [51]. This variable basically encompasses “the share of renewable energy in total energy consumption” as per the World Bank [50]. The energy transition data were retrieved from the WDI databank. This proxy of FinTech is taken by following the studies of Shahbaz et al. [51] and Topcu and Tugcu [21].

Another key variable used in the study is FinTech. This variable is constructed in index form from three variables that are extracted from WDI. These variables are mobile cellular and fixed broadband subscriptions and individuals using the internet. The first component of FinTech is the mobile subscription, which represents “subscriptions to a public mobile telephone service that provides access to the public switched telephone network using cellular technology”, and it includes (and is split into) the number of postpaid subscriptions and active counts prepaid accounts (i.e., used in the last three months). This definition pertains to any cellular phone subscription that includes voice communication services but excludes subscriptions for public mobile data services, private trunked mobile radio, telepoint, radio paging, and telemetry services. It also excludes subscriptions made through the use of data cards or USB modems. The second element of fintech is related to fixed broadband subscriptions, which refer to the provision of

reliable and constant high-speed access to the internet, with a downstream speed threshold of 256 kbit/s or more. This category encompasses various types of fixed subscriptions, such as cable modems, digital subscriber lines (DSL), fiber-to-the-home/building, satellite and terrestrial wireless broadband services. This also includes both residential subscriptions and subscriptions for organizations World Bank [50]. Similarly, the third component of FinTech used in the current study is internet use, measured as a percentage of the total population. This variable pertains to people who have utilized the internet within the previous three months, regardless of their location. The internet can be accessed through several devices, such as computers, mobile phones, personal digital assistants, gaming consoles, and digital TVs [50]. With the help of principal component analysis, the FinTech index is formed by compiling these three measures of technological advancements in financial sectors. This proxy of FinTech is taken by following the study of Emara [52]. Since FinTech heavily relies on the internet, the combination of these three distinct measures can better depict the adoption and integration of FinTech [37].

In addition to these core variables, the study also utilized control variables in the analysis. First, economic growth is used as a control variable in this study because of its significant impact on the energy transition. For this purpose, per capita gross domestic product is taken as a proxy variable of economic growth. This variable indicates the gross sum of the value added by all the producers residing in the economy plus product taxes and minus subsidies. The data are also taken from the World Development Indicators (WDI).

Second, population density is also included in the analysis. The proxy variable used for population density is population density (people per sq. km of land area). The data were collected from the WDI database. Third, the proxy variable of employers is “employers, total (% of total employment). Employers are workers who are self-employed or who work with a small group of partners to produce goods and services. These types of jobs are defined as “self-employment jobs”, where the income earned is directly based on the profits from the goods and services produced. In this capacity, they have hired one or more employees to work for them on a consistent basis. This definition was provided by the World Bank [50]. Fourth, industrial value added was also controlled for in the analysis while exploring the effects of FinTech and the government on the energy transition. This variable encompasses the value added in several industries, including mining, manufacturing, construction, electricity, water, and gas. It represents the final output of a sector after adding all the outputs and subtracting intermediate inputs. This definition was provided by the World Bank [50]. It is measured as a percentage of GDP. The data for industry value added are obtained from the WDI.

4. Results and discussions

4.1. Results of descriptive analysis

The results of the descriptive statistics in Table 2 show that most countries are relatively unequal, with an average Gini index of 43.197. The data are slightly skewed toward higher values for energy transition, with an average of 66.691. Most countries have small industries, with

an average of 24.954 for the share of industry in the economy. The population is concentrated in certain areas, with an average population density of 99.859 per km². Most countries have a low proportion of their active population employed, with an average of 2.113 for total employment. The level of development of FinTech is variable, with an average of 0.038 and strong positive skewness indicating the presence of outliers in some countries.

4.2. Results of correlation analysis

The results from Table 3 reveal significant inequality in the outcomes of SSA countries, with an average Gini index of 43.197, indicating that most countries are unequal. The correlation analysis shows a weak to moderately positive correlation between total employment and the inequality of outcomes, as well as an inverse correlation between energy transition and inequality. Population density has a significant negative correlation with inequality, total employment, and the share of industry in the economy. The level of development of FinTech has a weak correlation with all other variables, except for a significant negative correlation with population density. Economic growth and the share of industry in the economy do not have a significant correlation with the other variables. These results may help to understand trends in the selected variables, but further analysis is required to identify causal relationships between these variables.

4.3. Results of econometric analysis

This section presents the results of diagnostic tests and econometric modeling of the sample data. Table 4 presents the results of average correlation coefficients as well as the Pesaran CD test [38] to test for spatial autocorrelation of the study variables, namely, GINI, ET, EMP, IND, FINTECH, GDP, and POP. There are 45 groups, with an average of 19.97 observations.

The GINI variable has a weak and significant correlation coefficient of 0.9 and a p value of 0.04. The ET variable has a strong positive correlation of 0.403 with a p value of 0.00, indicating strong spatial autocorrelation. The EMP variable also has a significant positive correlation of 0.042 with a p value of 0.00, although it is weaker than that of ET. The IND variable has a significant positive correlation of 0.02 with a p value of 0.027, indicating weak to moderate spatial autocorrelation. FINTECH has a very strong and significant correlation of 0.958 with a p value of 0.00, indicating strong spatial autocorrelation with similar variation across groups. The GDP variable has a significant, moderate correlation of 0.245 with a p value of 0.00, indicating moderate spatial autocorrelation. Finally, the POP variable has an extremely strong and significant correlation of 0.919 with a p value of 0.00, indicating very strong spatial autocorrelation with similar variations in population. The Pesaran CD test shows that all variables are significantly spatially correlated.

The results of Wooldridge's autocorrelation test are presented in Table 5. These results show that for each variable—GINI, ET, FINTECH, GDP, POP, EMP, and IND—there is significant first-order autocorrelation in the data, with high F values and very low p values (0.00). This suggests that observations in each time series are correlated with their

Table 2
Descriptive Statistics.

Variables	Obs	Mean	Std. Dev.	Min	Max	Skew.	Kurt.
GINI	990	43.593	8.366	23.28	85.02	.975	4.487
ET	954	66.691	25.232	.71	98.34	−.971	2.914
FINTECH	990	−.377	1.458	−2.745	9.604	2.034	9.755
GDP	946	2029.087	2769.002	246.387	17117.026	2.766	10.935
POP	978	99.859	126.811	2.21	634.118	2.361	8.777
EMP	968	2.113	1.495	.049	8.394	1.116	4.101
IND	954	24.954	11.79	3.243	72.153	1.304	4.937

Table 3

Pairwise correlations.

Variables	GINI	ET	FINTECH	GDP	POP	EMP	IND
GINI	1.000						
ET	−0.301*	1.000					
FINTECH	−0.024	−0.597*	1.000				
GDP	−0.070	−0.009	−0.029	1.000			
POP	−0.150	−0.188*	0.231*	−0.014	1.000		
EMP	0.370*	−0.558*	0.367*	0.005	−0.028	1.000	
IND	0.282*	−0.093*	0.016	0.017	−0.357*	0.114*	1.000

Table 4

Cross-sectional dependence test.

Variables	CD-test	p value	Corr	Abs(Corr)
GINI	1.17	0.040	0.009	0.654
ET	55.11	0.000	0.403	0.568
FINTECH	133.66	0.000	0.958	0.958
GDP	34.47	0.000	0.245	0.423
POP	131.32	0.000	0.919	0.969
EMP	6.17	0.000	0.042	0.588
IND	2.22	0.027	0.020	0.421

Table 5

Wooldridge's autocorrelation test.

Variables	Test Statistics	p value
GINI	2194.657	0.0000
ET	170.862	0.0000
FINTECH	1301.101	0.0000
GDP	48.016	0.0000
POP	3908.078	0.0000
EMP	104.906	0.0000
IND	27.699	0.0000

own previous observations and that models envisioned for these data will have to take into account this autocorrelation.

The results of the Pesaran and Yamagata slope heterogeneity tests are presented in Table 6. The null hypothesis is that the slope coefficients are homogeneous. The results show that the delta test (19.866) and adjusted delta test (25.827) are highly significant (p value = 0.00), suggesting that the null hypothesis should be rejected. Therefore, there is strong evidence of heterogeneity in the slope coefficients of each variable. The constant variable was partially dropped to perform these tests.

To detect multicollinearity in the data, the variance inflation factor (VIF) is calculated in this study. Table 7 displays the outcomes of the multicollinearity assessment. The results present the VIF of each variable. VIFs help to detect collinearity among independent variables in a linear regression by indicating how much the variance of one variable is explained by other independent variables. Variables with a VIF greater than 5 are generally considered to have significant collinearity, while variables with a VIF greater than 10 have extremely significant collinearity. The results indicate that all variables have a VIF below 5, which indicates that there is no obvious collinearity among the variables. The average VIF is 1.45, which indicates that the variables are relatively distinct. Therefore, the results indicate that the variables can be used together in a linear regression model.

As it is well known from the diagnostic tests that the panel data used

Table 6

Slope homogeneity test.

Slope Statistics	Statistics Value	p value
Delta	19.866	0.000
Adj. Delta	25.827	0.000

Table 7

Multicollinearity test.

Variable	VIF	1/VIF
ET	2.14	0.468218
EMP	1.61	0.622035
FINTECH	1.48	0.675346
POP	1.30	0.768331
IND	1.18	0.849660
GDP	1.00	0.996906
Mean VIF	1.45	

in this analysis are characterized by issues of cross-sectional dependence, autocorrelation, and heterogeneity, this favors the econometric method of panel-corrected standard errors of Driscoll and Kraay [45]. Finally, the results of the panel econometric approach are summarized in Table 8. First, pooled OLSs are estimated as the base model, but as the cross-sectional units are not identical, this method provides biased results; hence, there are fixed effects and random effects. The results from the pooled OLS approach present a linear regression with Driscoll-Kraay standard errors. There are 862 observations, and 44 groups were identified with a maximum lag of 2. The results show a significant F-statistic of 143.45 with a p value of 0.0000, indicating that the independent variables have a significant influence on the dependent variable.

The results highlight the significant negative effect of the energy transition on income inequality in SSA countries. The coefficient for the transition to renewable energy (−5.10; $p < 0.01$) indicates that a one-unit increase in the energy transition indicator results in a 5.10% reduction in income inequality. This result is statistically significant at the 1% level. This study confirms the negative phenomenon found in previous literature regarding the relationship between energy transition and income inequality, as shown in the study by Topcu and Topcu [21]. However, this research stands out from previous works due to its enhanced methodology, which uses the panel-corrected standard errors approach for more accurate parameter estimation and better consideration of the correlation between sampling units. The underlying mechanism for this negative association can be attributed to the reduction in dependence on fossil fuels, which results in lower fossil fuel prices and reduced production costs for businesses and households. This, in turn, promotes more inclusive growth and a more equitable distribution of income. Furthermore, an energy transition encourages a more diversified economy, providing increased employment opportunities and better access to resources for underprivileged groups. By enabling greater participation in the economy and access to the benefits of economic growth, an energy transition can contribute to reducing income inequality in SSA countries.

The development of FinTech has a negative and statistically significant effect on income inequality in the study sample. The coefficient associated with the FinTech indicator (−1.31; $p < 0$) indicates that a one-unit increase in the FinTech indicator results in a 1.31% reduction in income inequality. This result is statistically significant at the 1% level.

Several factors may explain why FinTech reduces income inequality in Sub-Saharan Africa, including increased access to financial services,

Table 8

Estimation models POLS, FE, and RE for Income Inequality in SSA Countries.

Models Dependent Variable VARIABLES	Income Inequality	POLS	FE	RE
		Estimated Coefficients		
Energy transition		−5.100*** (0.474)	1.789 (2.102)	−1.013 (1.640)
Fintech		−1.315*** (0.107)	−0.792*** (0.167)	−0.917*** (0.138)
Economic Growth		0.309 (0.271)	−0.0289 (0.0977)	−0.0242 (0.129)
Population density		−0.00632*** (0.00146)	−0.000264 (0.00418)	−0.00423* (0.00217)
Employers		0.864*** (0.299)	0.671*** (0.176)	0.772** (0.290)
Industrial Value Added		0.129*** (0.0191)	0.0169 (0.0332)	0.0336 (0.0307)
Constant		56.90*** (2.331)	33.75*** (8.000)	45.03*** (6.523)
Observations		862	862	862
Hausman Test		10.16 (0.1182)		
Number of groups		44	44	44

Notes: ***, **, and * represent $p < 0,01$, $p < 0,05$ and $p < 0,10$ significance levels, respectively. Standard errors in parentheses are robust standard errors.

reduced transaction costs, the streamlining of credit processes, and transaction transparency. Indeed, FinTech allows for the provision of innovative financial services to populations who previously did not have access to them. For example, mobile money transfers allow individuals to send and receive money safely and quickly without needing a traditional bank account. This can improve low-income people's access to financial services and thus reduce income inequality. In addition, digital financial services such as mobile payments have the potential to reduce transaction costs for individuals and businesses compared to conventional payment methods. This can allow populations to pay less for financial services, reducing transaction costs and contributing to lower income inequality. Finally, FinTech innovation allows for the use of advanced technologies such as AI and blockchain. These technologies have the potential to streamline credit processes and reduce costs associated with lending for businesses and individuals. This can improve access to credit for low-income populations and promote job creation to reduce income inequality.

By combining these factors, FinTech helps to reduce income inequality by creating more financial opportunities for low-income individuals and businesses and streamlining credit and payment processes to reduce transaction costs. These results confirm the findings of previous studies on the role of FinTech in reducing income inequality, such as the study by Demir et al. [16]. However, our study differs from these studies through an improved approach consisting of using correlation between sampling units and providing more precise parameter estimation, which highlights the beneficial and innovative impact of FinTech technologies on income inequality in SSA countries.

Furthermore, the estimation reveals a negative and statistically significant impact of population density on income inequality in SSA countries. According to the results, an increase of one unit in population density reduces income inequality by 0.00632% in the sample economies. The result of the effect of population density on income inequality is consistent with the empirical findings of Perron [53].

This finding that population density reduces income inequality in Sub-Saharan Africa may seem surprising, as high population density is generally associated with greater inequality. Even so, this phenomenon can be explained by several factors. First, densely populated cities often offer more employment opportunities and increased access to public services such as education and healthcare. Cities can also offer easier access to financial services such as banks and credit cooperatives, as well as larger markets for small entrepreneurs. Second, population density can stimulate economic competition, which can reduce the prices of goods and services, thus offering economic benefits to the low-

income population. This competition can also promote product and service quality improvement, encourage innovation and grow local businesses. In addition, population density can encourage the exchange of skills and ideas, thus strengthening the capacity of local populations to innovate and create value. Population density can also worsen income inequalities if it is not managed appropriately. Rapidly growing cities can lead to the formation of slums, precarious employment and inadequate public services such as clean water and sanitation. Therefore, to ensure that population density effectively reduces income inequality, public policies must be implemented to manage the rapid growth of cities, provide quality services to all residents and promote social cohesion.

However, it is estimated that employers have a positive influence on income inequality in SSA countries. This result is consistent with the findings of the study conducted by Sørensen and Sorenson [54]. According to the calculated results, an increase of one unit in the EMP improves the GINI by 0.86%. This is because job creation can be concentrated in certain sectors or industries, and salaries can vary greatly according to the sector. In some cases, the jobs created may not be sufficiently remunerative for workers, which can lead to increased poverty and income inequality. For example, in South Africa, the mining sector, which employs a large number of workers, tends to offer higher wages than other sectors, which can contribute to greater income inequality among workers.

Additionally, the impact of industrial value added on income inequality is positive, as shown by the empirical studies of Moore [55] and Villanthenkodath [56]. The coefficient for industrial value added is statistically significant (0.129) in the current analysis. Furthermore, it should be noted that the link between industrial value added and income inequality may depend on national and regional economic policies. Economic policies that encourage industrial growth without adequate regulation can encourage wealth and value-added concentration in the hands of businesses and investors without offering social and economic benefits for low- and middle-income populations.

However, in some cases, economic growth associated with industrialization can lead to increased economic inequality. Economic gains can be captured by dominant elites rather than underpaid workers, thus fuelling growing inequalities. This is particularly the case when workers operate under low-paying conditions and in hazardous work environments without adequate social guarantees. Therefore, the relationship between industrial value added and income inequality (measured by the Gini index) in Sub-Saharan Africa depends on how economic policies are implemented. The positive correlation between

industrial value added and income inequality may largely be due to the economic and social priorities favored by each country. On the other hand, economic growth does not have a significant impact on income inequality (measured by the Gini index) in Sub-Saharan Africa. The constant is significant, with a basic interpretation of 56.90335.

5. Conclusion and policy implications

The study of the impact of energy transition and FinTech on income inequality is a critical issue in the global context of combating climate change and achieving the Sustainable Development Goals (SDGs) set by the United Nations, including SDG 10 (reducing inequality). While these factors have the potential to improve access to renewable energy and promote more inclusive economic growth, their impact on income inequality is not uniform, and several aspects require further investigation.

The analysis of 45 SSA economies revealed several important findings that contribute to the understanding of the synergistic relationships among energy transition, FinTech, and income inequality. By employing the panel-corrected standard errors approach, this study accounted for contextual and institutional factors, as well as regional specificities, covering the period from 2000 to 2021. The findings demonstrate the following:

- Transitioning to renewable energy sources leads to a 5.10% reduction in income inequality for every unit increase in the energy transition indicator. This highlights the potential for the energy transition to contribute to more inclusive and equitable economic growth, as it reduces carbon emissions and provides access to the benefits of sustainable energy.
- FinTech is associated with a 1.31% reduction in income inequality for every unit increase in the FinTech indicator. This positive correlation between FinTech and income inequality reduction indicates that the adoption of technological advances in the financial sector can support financial inclusion, promote economic growth, and offer better income distribution opportunities.
- A weak, yet statistically significant, correlation between population density and income inequality was found, with a one-unit increase in population density reducing income inequality by 0.00632%. This suggests that increased population density can be a factor in promoting income equality in the context of urban development.
- The study revealed a significant coefficient of 0.129 for industrial value added, indicating that a more developed industrial sector is associated with a lower income inequality level.

Overall, the findings emphasize the importance of considering contextual and institutional factors to maximize the potential benefits and minimize the negative effects of these developments on income inequality. This research has implications for public policies, the design of sustainable development strategies, the allocation of resources, and the understanding of the complex interplay between renewable energy, technology, and socioeconomic factors.

In conclusion, exploring the relationships among energy transition, FinTech, and income inequality is essential for promoting sustainable development and creating a more equitable global economic landscape. Uncovering the connections between financial innovation, renewable energy transition, and income inequality helps to address the UN's sustainable development goals and contributes to more informed and sustainable policymaking in the context of global climate change.

5.1. Policy implications

The policy implications drawn from the study's findings offer several

versatile strategies to support progressive fiscal policies, focusing on tax credits for renewable energy and financial incentives for affordable housing initiatives. Providing tax incentives for clean energy projects motivates businesses and individuals to invest in renewable energy technology, bolstering sustainable energy transition efforts. Similarly, housing subsidies or affordable financing can reduce income inequality by creating a better balance between the housing supply and demand, providing more equitable access to housing. Governments can further enhance financial inclusion by supporting FinTech initiatives aimed at providing affordable banking and financial services to low-income populations, reducing barriers to entry for disadvantaged individuals. This support can help foster an inclusive financial landscape and strengthen economic resilience. To encourage the adoption of renewable energy sources, governments can devise and implement financial designs offering awards or rebates, fostering the adoption of technologies that reduce carbon emissions. Furthermore, investing in infrastructure improvements in rural areas can facilitate the supply chain of clean energy and increase access to energy services for underprivileged communities. Finally, embracing policies that foster fair economic development and nurture local and regional economies can lead to growth and increased employment opportunities. Prioritizing economic inclusiveness, governments can steer industries toward more equitable business practices and enhanced cooperation, thereby elevating social welfare and stimulating long-term development. These policies collectively help construct more inclusive economic systems that promote a fair and sustainable transition to renewable energy.

5.2. Limitations and future recommendations

This study has certain limitations. The analysis relies on aggregated data and statistical models, which might not capture the diverse effects of changing energy landscapes and FinTech on different sets of people and social layers. The primary focus revolves around income inequality, with a tangential analysis of disparities in access to basic services and potential racial and ethnic inequality. To address these shortcomings, future studies can investigate the specific consequences of energy transition and FinTech on vulnerable demographics, including low-income communities, people of color, and indigenous populations. In-depth investigations to evaluate the effectiveness of public policies in tackling socioeconomic disparities in energy transition and fintech contexts can lead to improved understanding and dynamic solutions. Considering the multidimensional nature of inequality, it is important to study the effects of energy transition and FinTech on various domains, such as race, ethnicity, and gender. Consequently, future research can provide tailored and comprehensive insights into each aspect, making informed policy-making possible and addressing inequalities more holistically.

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 A. List of sample economies of sub-Saharan Africa (45 countries)

Angola	Cote d'Ivoire	Malawi	Sierra Leone
Benin	Eswatini	Mali	South Africa
Botswana	Ethiopia	Mauritania	South Sudan
Burkina Faso	Gabon	Mauritius	Sudan
Burundi	Gambia, The	Mozambique	Tanzania
Cabo Verde	Ghana	Namibia	Togo
Cameroon	Guinea	Niger	Uganda
Central African Republic	Guinea-Bissau	Nigeria	Zambia
Chad	Kenya	Rwanda	Zimbabwe
Comoros	Lesotho	Sao Tome and Principe	
Congo, Dem. Rep.	Liberia	Senegal	
Congo, Rep.	Madagascar	Seychelles	

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