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Research paper

The role of energy vulnerability in shaping human development outcomes: A multidimensional analysis

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ABSTRACT

Though African countries are experiencing progress in access to reliable, modern, and affordable energy sources, many African people remain vulnerable to energy access, which negatively impacts human development outcomes. This study investigates the effects of energy vulnerability on human development, measured by the Human Development Index (HDI), infant and under-five mortality, life expectancy, and human capital in 27 African countries over the 2000–2019 period. The Driscoll-Kraay standard errors, IV-GMM, and panel quantile regression methods are employed to account for cross-sectional dependence, heterogeneity, and endogeneity issues. The results indicate that a one percent increase in energy vulnerability is negatively associated with human development outcomes. Sub-regional analysis shows reliable and consistent findings. The findings of this study suggest expanding access to electricity, promoting the development of renewable energy sources and energy-efficient technologies, and investing in energy infrastructure and capacity building to improve the reliability and quality of energy services. Further research should examine mechanisms.

1. Introduction

This paper examines the role of energy vulnerability in shaping human development outcomes in African countries. The importance of addressing human development has been increasingly recognized by policymakers, researchers, and international organizations over recent decades. The United Nations Development Programme (UNDP, 1990) Human Development Report (HDR) pioneered a paradigm shift, arguing that a nation's true wealth lies in its people and that development should prioritize enabling long, healthy, and fulfilling lives. This perspective aligns with Amartya Sen's capability approach (Sen, 1999), which emphasizes the central role of functional capabilities, including access to quality health and education, in human development. According to the Human Development Report (HDR, 2023-24), African countries consistently rank lowest in human development. The Human Development Index (HDI), a composite measure of life expectancy, education, and per capita income, is widely used to assess progress. Data from 1990 to 2022 reveal that Sub-Saharan Africa (SSA) lagged significantly behind global averages, with HDI values of 0.404 in 1990 and 0.549 in 2022, compared to global means of 0.601 and 0.739, respectively. The COVID-19 pandemic further exacerbated this disparity. While most countries experienced a decline in 2020–2021, the subsequent recovery has been uneven, with a significant gap between developed and developing nations. For instance, in 2023, all Organisation for Economic Co-operation and Development (OECD) countries were projected to surpass their pre-pandemic HDI values, in contrast to only 49 % of Least Developed Countries (LDCs) (United Nations Development Programme, 2024). This disparity is particularly stark within low HDI countries, with only 48 % in Sub-Saharan Africa recovering to pre-pandemic levels, compared to 92 % of very high HDI countries (OECD).

Strong human development outcomes in developing countries are associated with robust economic growth, social cohesion, and trust in government and institutions, all of which contribute to achieving the 2030 Agenda for Sustainable Development (United Nations Development Programme, 2019; Opoku et al., 2022). Therefore, enhancing human development remains a critical priority in national and international development strategies.

There are Theoretical discussions on how energy accessibility can affect human development dimensions. First, energy is crucial in economic activities, including agriculture, manufacturing, and services (Badiani-Magnusson and Jessoe, 2018; Buisson et al., 2021). Limited access to reliable and affordable energy services hampers productivity

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and efficiency, lowering income levels for individuals and businesses. Energy constraints can limit job creation opportunities, especially in industries requiring electricity or other energy sources for operations. This can result in higher unemployment rates and reduced income-generating activities in communities affected by energy vulnerability (Owusu and Asumadu, 2016; International Renewable Energy Agency IRENA, 2018). Lack of access to energy services can hinder the growth of small businesses and entrepreneurship. Without a reliable power supply for lighting, machinery, and communication, entrepreneurs may struggle to establish and expand their businesses, impacting their income potential.

Second, energy shortages can disrupt the functioning of healthcare facilities, affecting the delivery of essential medical services (Rao and Pachauri, 2017). Lack of electricity for medical equipment, lighting, and refrigeration of vaccines and medicines can compromise patient care and health outcomes. Reliance on traditional energy sources like biomass for cooking and heating can lead to indoor air pollution, contributing to respiratory diseases and other health issues (Lam et al., 2012; World Health Organization, 2018). Poor indoor air quality due to inefficient energy use poses health risks, particularly for women and children who spend more time indoors. Energy is essential for water pumping, purification, and sanitation services. Energy vulnerability can impact access to clean water and proper sanitation facilities, increasing the risk of waterborne diseases and hygiene-related health problems in communities (Nguea, 2024a).

Third, energy insecurity can hinder access to education by limiting the availability of electricity in schools for lighting, heating, and powering educational tools (Rao and Pachauri, 2017; United Nations International Children's Emergency Fund, 2018). Students may struggle to study after dark or lack access to digital learning resources, affecting their academic performance and educational outcomes. Inadequate energy infrastructure in schools can impact the quality of education by disrupting teaching activities and hindering the use of technology for learning (Hansen et al., 2012; United Nations International Children's Emergency Fund, 2018). Schools without reliable power supply may face challenges in providing a conducive learning environment for students and teachers. Energy vulnerability can exacerbate the digital divide by limiting access to electricity for internet connectivity and digital learning tools. Students in energy-vulnerable areas may lack opportunities to develop digital literacy skills and access online educational resources, affecting their educational attainment and prospects.

Despite the importance of energy on human development outcomes in Africa, African countries have the lowest energy access in the world, according to the International Energy Agency (International Energy Agency IEA, 2022). According to the World Health Organisation (World Health Organisation (WHO), 2016), while 41 % of Africans have access to electricity, only 18 % rely on clean fuels and technologies for cooking, and the remaining 82 % rely on dirty fuels for cooking and heating. Furthermore, per capita electricity consumption in Africa is 10 times lower than in high-income countries, while the region's energy intensity is the highest (World Health Organisation, 2016). Over the past three decades, numerous studies have explored the influence of disaggregated energy vulnerability measures on human development. Those studies have explored the effect of energy poverty (Kanagawa and Nakata, 2008; Gohlke et al., 2011; Niu et al., 2013; da da Silveira Bezerra et al., 2017; Njiru and Letema, 2018; Oum, 2019), energy consumption (Ouedraogo, 2013; González-Eguino, 2015; Wang et al., 2019; Tran et al., 2019), renewable energy consumption (Pîrlogea, 2012; Wang et al., 2018; Fatima et al., 2019) and biomass energy consumption (Wang et al., 2020; Hung, 2021; Asghar et al., 2022, Nguea, 2023a). However, there is a noticeable gap in these previous studies that is addressed in this study.

This study makes several significant contributions. Firstly, it is the first to investigate and assess the impact of energy vulnerability on human development. Secondly, the study leverages the multidimensional nature of human development, encompassing education and health dimensions, to analyze the effects of energy vulnerability on different components of human development. Thirdly, this study utilizes the energy vulnerability developed by Liu et al. (2023) and Dong et al. (2024) to examine the effects of energy vulnerability on human development. Fourthly, this study runs a sub-regional analysis to capture heterogeneity across countries and identify specific patterns and trends within Sub-Saharan and Northern Africa regions. This can help policymakers design targeted interventions and policies that address each sub-region's energy vulnerability challenges and human development needs. Fifthly, to address issues such as heteroscedasticity, heterogeneity, cross-sectional dependence, and endogeneity, the study employs various econometrics methods to estimate this relationship. The subsequent sections of the study are structured as follows: Section 2 presents and describes data and methodology. Section 3 presents and discusses the study's results, while Section 4 concludes and provides policy implications.

2. Method

2.1. Data description

This study investigates the impact of energy vulnerability on 27 African countries between 2000 and 2019. The availability of the data dictates the sample and period of the study.

2.1.1. Dependent variables

The main dependent variable is human development, measured by the Human Development Index (HDI). The HDI is a composite index developed by the United Nations Development Programme (UNDP) to measure and compare the overall development levels of countries based on three key dimensions: health, education, and standard of living (United Nations Development Programme, 2021). The HDI provides a more holistic and multidimensional assessment of human well-being than traditional economic indicators like GDP per capita. The HDI combines multiple indicators to comprehensively measure human development, capturing both social and economic dimensions. First, life expectancy at birth is a proxy for overall health outcomes and access to healthcare services. Second, mean and expected years of schooling reflect educational attainment and access to quality education. Lastly, GNI per capita accounts for income levels and economic well-being, considering both material wealth and economic opportunities available to individuals. The HDI is based on the principle that development should be assessed in terms of improving people's capabilities and choices rather than focusing solely on economic growth (Haq, 1995; Nussbaum, 2000; Sen, 1999). Furthermore, the HDI allows for comparisons across countries and regions, highlighting disparities in human development outcomes and identifying areas for improvement.

Along with Opoku et al. (2022), Acheampong et al. (2021), and Nguea (2023a), we also use two out of three HDI dimensions—health and education. Life expectancy at birth (LEB), under-five mortality (Under), and infant mortality rate (IMR) are used to measure the health dimension. At the same time, human capital is employed as a measure of education. Life expectancy at birth can be a valuable measure of a population's overall health and well-being and is also considered an essential indicator of a country's living standard. A higher life expectancy generally indicates better access to healthcare, nutrition, sanitation, and other factors contributing to higher quality of life. The United Nations Children's Fund report (2018) has pointed out that life expectancy and the infant mortality rate are closely linked to a country's income level. Human capital is calculated as the average years of schooling and an assumed rate of return to education (Feenstra et al., 2015).

2.1.2. Main independent variable

This study relies on the Energy vulnerability index developed by Dong et al. (2024) and Liu et al. (2023) to measure energy vulnerability.

The Energy Vulnerability Index (EVI) is a tool used to assess the vulnerability of a population or region to energy-related challenges, such as energy poverty, insecurity, and lack of access to reliable and affordable energy sources. The EVI combines various indicators to provide a comprehensive measure of energy vulnerability, considering social, economic, environmental, and institutional factors influencing energy access and affordability. Appendix A2 presents the different sub-indicators used to compute the EVI. The authors use the Improved Entropy Method (IEM) to aggregate the different characteristics of energy vulnerability into an index. The index ranges from 0 (low vulnerability) to 100 (high vulnerability).

2.1.3. Control variables

To prevent omitted variable bias, four control variables are introduced into the model: Democracy, ICT, Industrialization, and population size. Democracy is captured by the Liberal democracy index (Libdem) from the Variety Democracies (V-Dem) database developed by Coppedge et al. (2018). This index expresses the significance of protecting individual and minority rights against the tyranny of the state and the tyranny of the majority (Coppedge et al., 2018). Democratic institutions provide a stable and predictable environment for investment and economic growth, which can lead to improved living standards (Kaufman and Segura-Ubiergo, 2001; Lake and Baum, 2001; Kudamatsu, 2012; Nguea et al., 2023). The number of individuals using the Internet (% of the total population) is included to capture the effect of ICT on human development. The internet fosters social change and leads the growth of e-commerce, remote work, and online education, creating job opportunities that lead to better human development outcomes (Asongu and Le Roux, 2017; Nguea, 2023a). Industrialization is captured by manufactured value added (%GDP). Lying at the heart of structural change and the accompanying economic growth and development (World Bank, 2021), industrialization has always been an important aspiration for Africa due in part to the existence of the continent's young labor force, abundant natural resources, and rapidly expanding domestic markets. According to Mendes (2022), Africa continues to be promoted as the world's 'next industrial frontier'. The total population measures population size. A larger population can provide a larger workforce, increased demand for goods and services, and economies of scale (Nguea, 2024b), while rapid population growth can strain resources, lead to environmental degradation, and hinder the provision of essential services (Ahlburg, 1996).

2.2. Model specification

Energy vulnerability, which refers to the lack of access to reliable, modern, efficient, and affordable energy sources, can significantly affect human development. When individuals or communities do not have access to energy, they may face challenges in meeting their basic needs, such as heating their homes, cooking food, or accessing clean water. This can negatively impact health, education, and overall quality of life (Nguea, 2024b; Acheampong et al., 2021). Energy vulnerability can also influence a country's overall development indicators. For instance, inadequate energy access can hinder economic growth, limit access to modern technologies, and impede efforts to achieve sustainable development goals (Ouedraogo, 2013; González-Eguino, 2015; Wang et al., 2019).

Given these arguments, the human development function is expressed as a function of energy vulnerability and a set of control variables. The generic model is expressed as follows:

$$HD_{it} = f(EVI_{it}, \quad X_{it}) \tag{1}$$

Where HD is human development captured by five indicators: HDI, infant mortality rate, life expectancy at birth, under-5 mortality rate, and human capital. EVI is the energy vulnerability index, and X is the vector of control variables. i and t refer to countries and time, respectively.

By decomposing the vector of control variables, Eq. 1 becomes:

$$HD_{it} = \beta_0 + \beta_1 EVI_{it} + \beta_2 Libdem_{it} + \beta_3 Internet_{it} + \beta_4 Industry_{it} + \beta_5 Population_{it} + \mu_i + \varphi_t + \varepsilon_{it}$$

Where *Libdem*Is the liberal democracy index, *Internet* is the Internet users, *Industry*Is the industry value added (%GDP), and *Population* is the size of the population. $\mu_i, \ \varphi_t and \varepsilon_{it}$ are the individual fixed-effect, time fixed-effect, and error-term, respectively. β_0 is the constant, $\beta_1 - \beta_5$ are the elasticities.

2.3. Estimation techniques

This study uses three estimation techniques for empirical investigations. We first use Driscoll-Kraay's (1998) standard errors to estimate our econometric model. This method corrects standard errors for heteroscedasticity, autocorrelation, and cross-sectional dependence in panel data models (Hoechle, 2007). It assumes that the errors are serially correlated up to a particular order. It also uses a non-parametric method to estimate the covariance matrix of errors, which is then used to calculate robust standard errors. Though the Driscoll-Kraay method is helpful in panel data, as indicated above, it does not correct for endogeneity in panel data models. We use the Instrumental Variable (IV) Generalized Method of Moments (IV-GMM). In the first step, this method uses instrumental variables to estimate the endogenous variables. In contrast, in the second step, the estimated endogenous variables are used as instruments in the GMM estimation of the model (Baum et al., 2003). IV-GMM also produces consistent and efficient estimates even in the presence of endogeneity and heteroscedasticity. The IV-GMM estimator has been utilized in previous studies (Adams & Acheampong, 2019; Boateng et al., 2021; Opoku et al., 2022; Nguea, 2023a). Though methods mentioned above are suitable for addressing panel data issues, including autocorrelation, heteroscedasticity, cross-sectional dependence, and endogeneity, they have some disadvantages compared to novel econometric methods such as Augmented Mean Group (AMG) and Cross-Correlated estimator Mean Group (CCEMG). While Driscoll and Kraay's standard errors may be less efficient, IV-GMM requires valid instruments. Our unbalanced panel using Driscoll and Kraay and IV-GMM is a good choice compared to AMG and CCEMG, which are unsuitable for addressing endogeneity issues (AMG and CCEMG) and unbalanced panel (AMG). Lastly, Driscoll-Kraay and IV-GMM fail to estimate the heterogeneous effects of energy vulnerability across different quantiles of the human development outcome and analyze non-linear relationships. The panel quantile regression method allows for the estimation of the conditional quantiles of the dependent variable at different points of the distribution. By capturing the heterogeneous effects across different quantiles of dependent variables, this study provides a more complete picture of the relationship between energy vulnerability and human development outcomes. This method has been used in previous studies (Nguea, 2023a; Opoku et al.,2022; Chen et al., 2024).

3. Results and discussions

3.1. Preliminary results

Table 1 displays the descriptive statistics and sources of the variables utilized in the models. Table (1) shows that the Mean of human development is 0.53, while the standard deviations of 11.4 % (HDI) indicate that there may be considerable variation in human development across different countries. This disparity highlights the need for targeted interventions to improve human development. Lastly, an EVI's mean score of 34.590 suggests that while the vulnerability of energy systems is relatively low, policies to mitigate energy vulnerability are crucial. The standard deviation of 14.02 indicates variability in the vulnerability of the energy system, which affects energy access.

Table 1
Descriptive Statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max	Sources
Human Development Index	537	0.536	0.114	0.262	0.804	UNDP (2023)
Infant Mortality Rate	540	46.016	0.504	12.490	121.875	WDI (2023)
Life Expectancy Birth	540	59.620	0.132	43.034	76.861	WDI (2023)
Under-five mortality rate	540	67.559	0.616	14.599	228.377	WDI (2023)
Human Capital	540	1.905	0.460	1.117	2.938	Feenstra et al. (2015)
Energy Vulnerability Index	540	34.590	14.042	9.460	59.033	Liu et al. (2023)
Liberal democracy index	540	0.328	0.198	0.017	0.73	Coppedge et al. (2020)
Internet	528	4.787	1.773	0.006	84.099	WDI (2023)
Industry	525	3.826	1.188	0.021	49.849	WDI (2023)
Population	540	16.734	1.254	1.185	203.260	(million) WDI (2023)

Source: Authors' calculations from Stata 17.

Fig. 1 illustrates the average HDI of African countries from 2000 to 2019. Mauritius boasted the highest average HDI at 0.74, followed closely by Algeria and Tunisia at 0.70 each, Egypt at 0.66, and South Africa at 0.65. Additionally, Gabon and Botswana registered an average HDI of 0.65 each, Morocco at 0.61, Namibia at 0.58, and Ghana at 0.55. Mauritius, Algeria, and Tunisia stand out as countries with an average HDI in the high range of 0.70–0.80. Furthermore, Egypt, South Africa, Gabon, Morocco, Namibia, and Ghana achieve average HDI within the medium human development range of 0.55–0.69. The remaining countries in the analysis fall within the low HDI average.

Fig. 2 presents the average EVI of African countries from 2000 to 2019. The figure reveals that Mauritius is the least vulnerable country between 2000 and 2019, followed by Tunisia, Egypt, Algeria, and Morocco. Fig. 2 suggests that the Democratic Congo, Tanzania, Niger, Tanzania, and Mozambique are the most vulnerable countries in access to reliable, modern, efficient and affordable energy sources. Upon close examination of this figure, it becomes apparent that 4 out of 5 countries with the lowest EVI are located in Northern Africa (Algeria, Tunisia, Egypt, and Morocco). This difference between SSA countries and Northern Africa could have different implications for human development outcomes. Addressing energy vulnerability in Africa is essential in enhancing human development in the region. Improving access to modern energy services, developing sustainable infrastructure, and promoting renewable energy sources can positively influence African human development indicators.

Table 2 shows the correlation between data. The correlation table results indicate that all coefficients are less than 0.8, suggesting that the data is well-suited for making accurate estimates. The coefficient of correlation between HDI and EVI is negative, confirmed by Fig. 3. The negative relationship between energy vulnerability and human development indicates that as energy vulnerability increases (e.g., due to lack of access to reliable and affordable energy services), the human development index tends to decrease, meaning that countries facing higher levels of energy vulnerability are likely to experience lower levels of human development in terms of income, health, and education.

3.2. Cross-sectional dependence and panel unit root tests

Cross-sectional dependence and panel unit root tests were conducted to validate and enhance the efficiency of the estimated results. The presence of cross-sectional dependence was confirmed using the Pesaran (2004) CD test. Additionally, the panel unit root test indicated that all variables exhibited a unit root in their levels, while none of the data showed a unit root in their difference.

3.3. Baseline results

The results reported in Table 5 show that energy vulnerability negatively and significantly impacts human development and its dimensions. African countries lack access to modern, affordable, and efficient energy sources, so their human development outcomes are low. Energy vulnerability limits access to essential healthcare services, such as prenatal care, delivery assistance, and immunization. Lack of access to electricity and clean cooking fuel increases the risk of indoor air pollution, leading to respiratory infections and other health problems in infants and young children. Furthermore, poor lighting and refrigeration

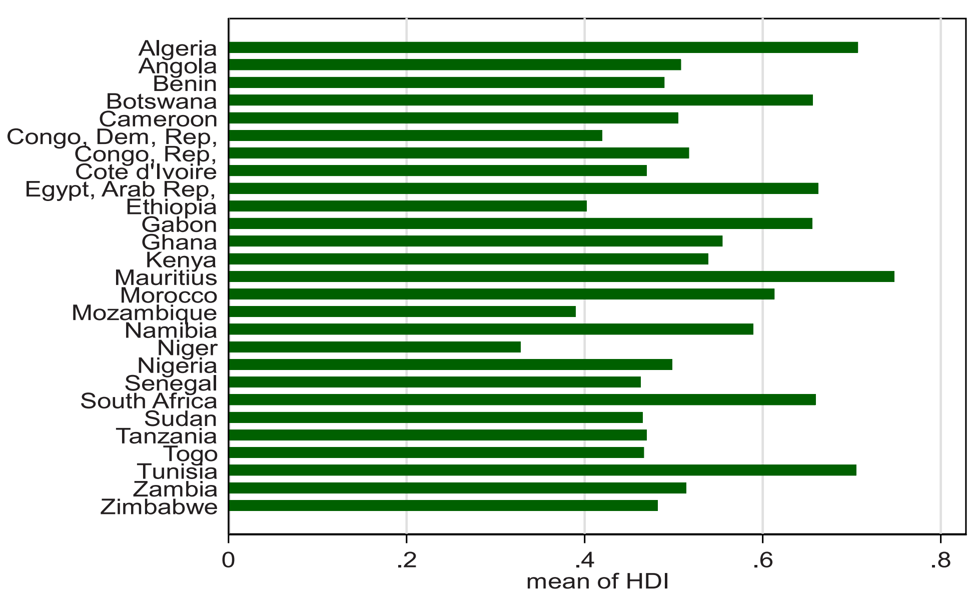

Fig. 1. The average HDI of African countries for 2000–2019.
Source: Generated by authors using Stata 17

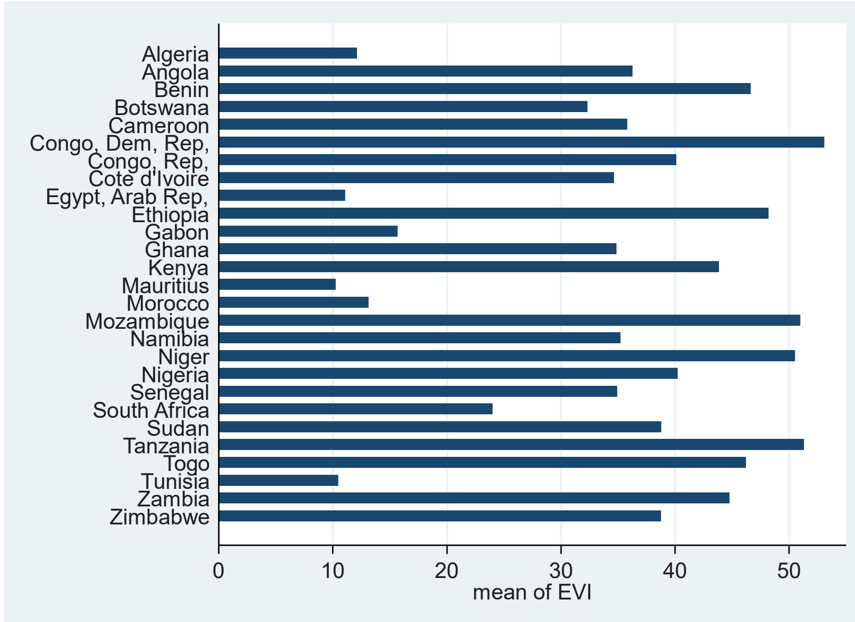

Fig. 2. The average EVI of African countries for 2000–2019.
Source: Generated by authors using Stata 17

Table 2
Correlation matrix.

	HDI	IMR	LEB	Under	HC	EVI	Libdem	Internet	Industry	Population
HDI	1									
IMR	−0.834	1								
LEB	0.738	−0.824	1							
Under	−0.871	0.971	−0.868	1						
HC	0.788	−0.605	0.349	−0.609	1					
EVI	−0.839	0.827	−0.771	0.853	−0.523	1				
Libdem	0.269	−0.257	0.085	−0.204	0.321	−0.052	1			
Internet	0.761	−0.673	0.648	−0.702	0.559	−0.567	0.276	1		
Industry	0.107	−0.017	0.231	−0.066	−0.041	−0.102	−0.223	0.0003	1	
Population	−0.269	0.241	−0.048	0.197	−0.363	0.164	−0.337	−0.062	0.010	1

Source: Authors' calculations from Stata 17.

hinder proper food storage and preparation, contributing to malnutrition and increased risk of infant and under-five mortality. Energy vulnerability hinders educational opportunities, as lack of electricity limits access to lighting for studying and ICT for learning. Poor indoor air quality due to inefficient cooking fuels can impair cognitive development in children. Energy poverty can lead to time poverty, as individuals spend excessive time collecting fuel or relying on inefficient energy sources, diverting time away from productive activities such as education and income-generating work. These results differ from the one of Acheampong et al. (2021), whose study reveals that access to electricity and clean energy improves human development in SSA.

Energy vulnerability reduces access to clean water and sanitation, increasing the risk of waterborne disease and other health issues. At the same time, it can also lead to unsafe lighting and cooking practices, resulting in accidents, burns, and injuries. For instance, in rural Ethiopia, households without access to electricity have a 25 % higher infant mortality rate than those with electricity. In contrast, children living in energy-poor households are 1.5 times more likely to die before the age of five. Energy vulnerability is a major obstacle to human development In Africa, contributing to high infant and under-five mortality, reduced life expectancy, and diminished human capital. Mitigating energy vulnerability through investments in energy infrastructure to expand access to reliable and affordable energy sources is crucial for improving health outcomes, educational opportunities, and overall well-being. These results align with Niu et al. (2013) and Ouedraogo (2013). While the adverse effects are apparent, it is crucial to analyze the nuances critically. The specific impact may vary based on geographical location, the type of energy used, existing infrastructure, and governance. Furthermore, simply providing access to energy without considering sustainability, affordability, and equitable distribution can lead to new challenges. Effective solutions must be tailored to local contexts and incorporate participatory approaches involving communities and stakeholders. Lastly, addressing energy vulnerability requires financial and technological solutions and a significant focus on strengthening governance.

Another factor contributing significantly to human development outcomes is democracy, which has a positive impact, suggesting that an increase in democracy will increase HDI, life expectancy, and human capital and reduce infant and under-five mortality in Africa. Democracy empowers citizens to participate in decision-making and hold their leaders accountable. This can make policies and programs more responsive to the population's needs and promote human development. This result is supported by (Ross, 2006; Wigley and Akkoyunlu-Wigley, 2017). The coefficients of the Internet imply a positive effect of ICT on human development outcomes, increasing HDI, life expectancy, and human capital and reducing infant and under-five mortality. This result is consistent with Bankole et al. (2011) and Acheampong et al. (2022). The impact of industrialization on human development outcomes

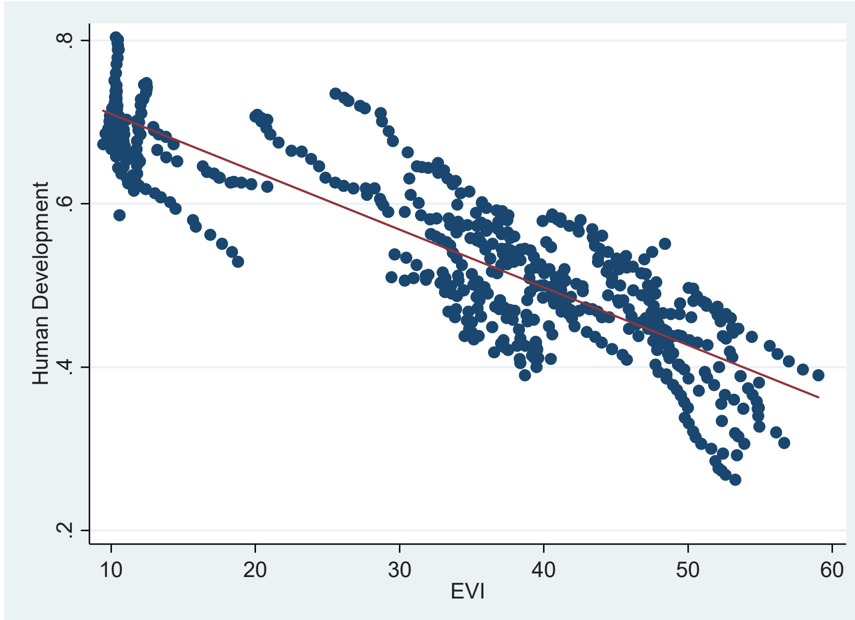

Fig. 3. Plots of Human development against EVI.
Source: Generated by authors using Stata 17

Table 3
Cross-sectional dependence test results.

Variable	CD-test	P-value	Corr	abs(Corr)
Human Development Index	81.23	0.000	0.975	0.975
Human capital	81.33	0.000	0.976	0.976
Energy Vulnerability Index	50.26	0.000	0.604	0.832
Infant mortality rate	69.91	0.000	0.840	0.843
Life Expectancy at Birth	79.26	0.000	0.970	0.970
Under-five mortality rate	77.24	0.000	0.946	0.946
Liberal democracy	11.15	0.000	0.139	0.439
Internet	77.32	0.000	0.946	0.946
Industry	57.56	0.000	0.609	0.414
Population	72.75	0.000	0.896	0.899

Source: Authors' calculations from Stata 17.

Table 4
Unit root test.

	Pesaran's CADF test	
	Level	Difference
HDI	0.304	−3.078***
IMR	−1.624	−2.692**
LEB	−3.189***	−3.701***
Under	−1.677	−2.069**
HC	−1.004	−3.049***
EVI	−2.854***	−5.201***
Libdem	−2.145	−4.128***
Internet	−1.303*	−8.380***
Industry	−6.431***	−14.248***
Population	−2.766***	−3.456***

Notes:
** $p < 0.05$;
*** $p < 0.01$,
Source: Authors' calculations from Stata 17.

appears positive and significant, implying that industrialization effectively improves people's living conditions. Industrialization creates new industries and job opportunities, particularly manufacturing, transportation, and construction. This can increase employment rates and higher wages, increase access to goods and services, and improve human development. These findings follow the results of (Oyelaran-Oyeyinka, 2014; Chang and Zach, 2019). The coefficient attached to population indicated a positive effect of population on human development outcomes. This can be explained by the fact that a larger population creates a larger market for goods and services, stimulating economic activity and job creation. Furthermore, a larger population can lead to economies of scale in providing public services, such as education, healthcare, and infrastructure. This result is consistent with those found by Noumba et al. (2022).

3.4. Panel quantile results

Standard econometric approaches assume that the relationship between dependent and independent variables is linear and that the error term is normally distributed. However, these assumptions do not always hold in practice. Panel quantile regression corrects standard econometric approaches by estimating the conditional quantiles of the dependent variable rather than the conditional mean. It allows for the non-linear relationship between the dependent and independent variables. This is important because many economic and social phenomena exhibit non-linear patterns. To account for the non-linear relationship, we rerun baseline results using the generalized quantile regression method (Powell, 2020), implemented within an IV framework to account for potential endogeneity issues. The findings are reported in Table 6. The results are grouped into three quantiles according to the level of human development outcome: Low (10th-30th), Medium (40th-60th), and High (70th-90th). Panels A, B, C, D, and E present the results for HDI, infant mortality, life expectancy, under-five mortality, and human capital, respectively. The results are generally consistent with those obtained using standard econometric methods. However, the quantile regression results suggest that the negative impact of energy vulnerability is decreasing in countries with high human development outcomes. The decreasing impact of energy vulnerability on human development outcomes in a country with high human development could be related to better infrastructure, resources, and systems to mitigate the adverse effects of energy vulnerability. Furthermore, countries with high human development outcomes may have more robust institutions and governance structures that respond effectively to energy vulnerability.

Table 5
Baseline results.

	Driscoll-Kraay					IV-GMM				
	HDI	IMR	LEB	Under	HC	HDI	IMR	LEB	Under	HC
EVI	−0.069***	0.380***	−0.135***	0.716***	−0.466***	−0.063***	0.372***	−0.130***	0.635***	−0.370***
	(0.011)	(0.050)	(0.014)	(0.074)	(0.071)	(0.006)	(0.041)	(0.008)	(0.053)	(0.042)
Libdem	0.015***	−0.144***	−0.039	−0.101*	0.424***	0.018***	−0.134***	−0.035***	−0.086**	0.407***
	(0.005)	(0.044)	(0.023)	(0.051)	(0.069)	(0.002)	(0.035)	(0.013)	(0.038)	(0.059)
Internet	0.022***	−0.029***	0.027***	−0.092***	0.040***	0.014***	−0.041***	0.013***	−0.056***	0.034***
	(0.001)	(0.004)	(0.002)	(0.007)	(0.003)	(0.001)	(0.004)	(0.004)	(0.005)	(0.002)
Industry	0.002	−0.002	0.009***	−0.014***	−0.005	0.003**	−0.007**	0.010***	−0.016***	−0.010
	(0.001)	(0.005)	(0.003)	(0.004)	(0.009)	(0.001)	(0.003)	(0.002)	(0.005)	(0.007)
Population	0.033	−0.795***	0.089**	−0.298**	0.068	0.128***	−0.713***	0.248***	−0.774***	0.227***
	(0.023)	(0.019)	(0.040)	(0.134)	(0.058)	(0.016)	(0.035)	(0.034)	(0.049)	(0.045)
Cons	−0.141	17.609***	2.408***	10.225***	0.030					
	(0.379)	(0.278)	(0.668)	(2.197)	(0.902)					
R^2	0.86	0.82	0.72	0.87	0.61					
Obs	515	518	518	518	518	483	485	485	485	485
Hansen-J						0.268	0.179	0.559	0.182	0.109

Notes: Standard errors in parentheses,
* $p < 0.1$
** $p < 0.05$
*** $p < 0.01$,
Source: Authors' calculations from Stata 17.

Table 6
Non-linear relationship.

	Dependent variable: Human Development Indicators								
	Low			*Medium*			*High*		
	10th	20th	30th	40th	50th	60th	70th	80th	90th
Panel A: Human Development Index									
EVI	−0.070***	−0.064***	−0.054***	−0.063***	−0.052***	−0.053***	−0.093***	−0.080***	−0.054***
	(0.00002)	(0.0004)	(0.0002)	(0.001)	(0.0004)	(0.0002)	(0.001)	(0.001)	(0.0001)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Panel B: Infant mortality rate									
EVI	0.289***	0.314***	0.270***	0.253***	0.204***	0.243***	0.191***	0.174***	0.241***
	(0.0004)	(0.003)	(0.0009)	(0.002)	(0.001)	(0.003)	(0.003)	(0.002)	(0.001)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Panel C: Life expectancy at birth									
EVI	−0.118***	−0.157***	−0.151***	−0.109***	−0.080***	−0.053***	−0.050***	−0.054***	−0.023***
	(0.0003)	(0.0009)	(0.0003)	(0.0005)	(0.0004)	(0.0005)	(0.0003)	(0.0009)	(0.0002)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Panel D: Under-five mortality rate									
EVI	0.640***	0.641***	0.714***(0.001)	0.594***	0.540***	0.596***	0.712***	0.744***	0.633***
	(0.004)	(0.001)		(0.002)	(0.004)	(0.003)	(0.002)	(0.007)	(0.0007)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Panel E: Human capital									
EVI	−0.556	−0.543***	−0.520***	−0.494***	−0.474***	−0.470***	−0.471***	−0.528***	−0.519***
	(0.001)	(0.002)	(0.001)	(0.001)	(0.002)	(0.001)	(0.001)	(0.0006)	(0.0006)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Standard errors in parentheses,
*** $p < 0.01$.
Source: Authors' calculations from Stata 17.

3.5. Heterogeneity analysis

To check whether the effect of energy vulnerability on human development differs between Sub-Saharan Africa and Northern Africa, a sub-regional analysis is running between Sub-Saharan Africa and Northern Africa. This is important for several reasons. First, Sub-Saharan and Northern Africa are distinct regions with different economic, social, and environmental characteristics. This can provide insights into the effectiveness of different approaches to addressing energy vulnerability and promoting human development. A study by the International Energy Agency (International Energy Agency IEA, 2022) showed that a 10 % increase in electricity access in SSA leads to a 5 % reduction in under-five mortality rates. However, in Northern Africa, the impact of electricity access on under-five mortality is less pronounced. Furthermore, the World Bank (2021) indicated that households without access to electricity in SSA have a 25 % higher probability of using improved sanitation facilities and a 15 % higher probability of using improved water sources compared to households with access to electricity access. In contrast, the relationship between electricity access and improved sanitation and water use is weaker in Northern Africa. The results presented in Table 7 show that energy vulnerability has a negative and significant impact on human development outcomes in both sub-regions. These results follow benchmark results, suggesting that regional policies effectively address energy vulnerability and promote human development in SSA and Northern Africa. However, the size of the effect of EVI on human development outcomes is more pronounced in SSA countries than in Northern Africa. These results confirmed the results found using panel quantile regressions.

Table 7
Result of the sub-regional analysis.

	Driscoll-Kraay					IV-GMM				
	HDI	IMR	LEB	Under	HC	HDI	IMR	LEB	Under	HC
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Northern Africa										
EVI	−0.080***	0.675***	−0.059***	0.654***	0.009	−0.088***	0.724***	−0.056***	0.701***	0.074***
	(0.014)	(0.097)	(0.008)	(0.096)	(0.050)	(0.012)	(0.091)	(0.003)	(0.081)	(0.022)
Baseline controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Hansen J-test						0.157	0.137	0.199	0.140	0.335
Observations	87	87	87	87	87	81	81	81	81	81
Countries	5	5	5	5	5	5	5	5	5	5
Sub-Saharan Africa										
EVI	−0.074***	0.182***	−0.210***	0.798***	−0.740***	−0.060***	0.166***	−0.199***	0.655***	−0.674***
	(0.428)	(0.031)	(0.027)	(0.074)	(0.080)	(0.007)	(0.022)	(0.021)	(0.046)	(0.039)
Baseline controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Hansen J-test						0.497	0.163	0.578	0.119	0.349
Observations	428	431	431	431	431	404	404	404	404	404
Countries	4	4	4	22	22	4	4	4	4	4

Notes: Standard errors in parentheses,
*** $p < 0.01$.
Source: Authors' calculations from Stata 17

4. Conclusion and Policy Implications

Energy vulnerability is a major obstacle to human development in Africa, while energy access can be a powerful driver of progress. This study investigates the effect of energy vulnerability on human development in 27 African countries over the 2000–2019 period. Driscoll-Kraay standards errors, IV-GMM, and panel quantile regressions are employed to correct heteroscedasticity, autocorrelation, heterogeneity, and endogeneity in panel data. The results show that energy vulnerability negatively affects human development outcomes by reducing the human development index, increasing infant and under-five mortality, and reducing life expectancy and human capital. The results also show that democracy, ICT, industrialization, and population positively enhance human development. Sub-regional analysis shows that these results are robust in Sub-Saharan and Northern Africa.

The reducing effect of energy vulnerability on human development in Africa demonstrates the crucial role of energy in achieving human development goals. It challenges established development theories by emphasizing the interconnectedness of energy with broader development objectives. It underscores the need for context-specific, holistic approaches that acknowledge the interplay of social, economic, and environmental factors. Some critical policy implications include:

1. Investment in Energy Infrastructure: Governments in Africa must prioritize investments in energy infrastructure to improve access to reliable and affordable energy sources. This includes expanding electricity grids, promoting off-grid solutions such as solar power, and investing in renewable energy projects. Policy measures such as public-private partnerships, regulatory reforms, and financial incentives can help attract investments in energy infrastructure and accelerate the transition toward a more sustainable energy system.
2. Energy Access Policies: Developing and implementing energy access policies prioritizing universal access to clean and affordable energy services is essential for reducing energy vulnerability in Africa. Governments can set targets for increasing electrification rates, promoting energy efficiency measures, and expanding access to modern cooking fuels. Policy frameworks that support decentralized energy solutions promote community-based initiatives, and address energy poverty can help ensure that all individuals have access to reliable energy sources for their basic needs.
3. Promotion of Renewable Energy: Encouraging the adoption of renewable energy sources such as solar, wind, and hydropower is crucial for reducing energy vulnerability and promoting sustainable development in Africa. Governments can implement policies that incentivize deploying renewable energy technologies, support research and development in clean energy solutions, and create enabling environments for renewable energy investments. By prioritizing renewable energy sources, African countries can reduce their dependence on fossil fuels, mitigate climate change impacts, and enhance energy security.
4. Energy Efficiency Regulations: Implementing energy efficiency regulations and standards can help reduce energy consumption, lower energy costs, and improve the overall efficiency of African energy systems. Governments can introduce policies that promote energy-efficient appliances, buildings, and industrial processes and provide incentives for adopting energy-saving technologies. By prioritizing energy efficiency measures, countries in Africa can reduce their energy demand, lower greenhouse gas emissions, and enhance the sustainability of their energy systems.
5. Capacity Building and Skills Development: Investing in capacity building and skills development in the energy sector is essential for ensuring the successful implementation of policies to reduce energy vulnerability in Africa. Governments can support training programs, technical assistance initiatives, and knowledge-sharing platforms to build the capacity of local communities, businesses, and institutions in the energy sector. By investing in human capital development, African countries can enhance their ability to plan, implement, and monitor energy policies effectively and sustainably.

While this study provides valuable insights, several limitations should be considered. The analysis was constrained by the availability of reliable and consistent data across all 27 countries for the entire study period. This could affect the accuracy and generalizability of the findings. This study does not investigate the channels through which energy vulnerability affects human development, while other essential variables in the African context, such as the weight of the public sector, infrastructures, consumer spending, etc. In contrast, this study utilizes a composite index of energy vulnerability. However, it does not explicitly analyze the distinct contributions of access, affordability, sustainability, and supply vulnerabilities to human development outcomes. Future research could build upon this study by: first, including a wide range of countries and more extended time series data could enhance the generalizability and the robustness of the findings; second, assessing the transmission mechanism and the effectiveness of different energy policies in different contexts is crucial for informing effective interventions; third, investigating the differential effects of different energy sources on human development. Addressing these limitations and pursuing future research can achieve a more comprehensive understanding of the multifaceted relationship between energy vulnerability and human development in Africa

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.

Appendix

Table A1
List of countries

Algeria	Ethiopia	Nigeria
Angola	Gabon	Senegal
Benin	Ghana	South Africa
Botswana	Kenya	Sudan
Cameroon	Mauritius	Tanzania
Congo, Democratic Republic	Morocco	Togo
Congo, Republic	Namibia	Tunisia
Côte d'Ivoire	Mozambique	Zambia
Egypt	Niger	Zimbabwe

Table A2
List of variables used to compute the EVI

Dimensions	Indicator	Definition and source
Energy access	Electricity acquisition	Access to electricity as a percentage of the population (Liu et al.,2023).
	Time to obtain power	The number of days with permanent power connection (Liu et al.,2023).
	Reliance on clean fuels and technologies	This refers to the proportion of people who rely mainly on clean fuels and technologies (95 or more and five or fewer are replaced by 95 and 5, respectively) (Liu et al.,2023).
Energy efficiency	Energy intensity	It required energy consumption to produce one unit of economic output (MJ/USD) (Liu et al.,2023).
	GDP per unit of energy use	PPP GDP per kilogram of oil equivalent of energy use (USD/kg of oil equivalent) (Liu et al.,2023).
	Overall system conversion efficiency	$OSCE=\frac{Final\ energy\ consumption}{Total\ primary\ energy\ supply}*100$;Efficient system transformation can reliably and efficiently meet society's current and future needs (Iddrisu and Bhattacharyya, 2015).
Renewable energy	Renewable energy	The share of renewable energy of total final energy consumption (Liu et al.,2023).
	Alternative and nuclear energy	The share of alternative and nuclear energy of total energy use (Liu et al.,2023).
	Fossil fuel energy	The share of fossil fuel energy consumption of total energy consumption (Liu et al.,2023).
	Renewable electricity output	The share of electricity generated from renewable energy plants of all electricity generated (%).
Total energy consumption	Electric power consumption	The output of power plants and cogeneration plants, excluding transmission, distribution, and substation losses, and the self-consumption of cogeneration plants (kWh per capita) (Liu et al.,2023).
	Energy use	Primary energy use before conversion to other end-use fuels (kg of oil equivalent per capita) (Liu et al.,2023).
Energy security	The CO2 content of primary energy	$CO_{2\text{-}P}=\frac{Total\ CO2emissions}{Total\ primary\ energy\ supply}$;Countries with a high dependence on fossil fuels are more likely to be affected by future energy and climate policies (tonnes/TJ) (Liu et al.,2023).
	Energy mix diversity	$SWI = -\sum_{i=1}^{n} P_i * \ln(P_i)$, P_i represents the proportion of energy i of total energy (Liu et al.,2023).
	Energy imports	The percentage of energy imports of energy use (%) (Liu et al.,2023).
	Fuel exports	Fuel exports are a share of merchandise exports. Fuel exports are a decisive factor in a country's power embedding, indicating a reduced vulnerability (%) (Gatto and Busato, 2020).

Source: Adapted from Liu et al. (2023)

Data availability

Data will be made available on request.

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