EFFECTS OF ENERGY DIVERSIFICATION IN SUB-SAHARAN AFRICA

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Abstract
The objective of this paper is to analyze the effect of energy diversification on child health in sub-Saharan African countries selected due to their energy vulnerability and the challenges related to accessing modern energy sources. Using data from 1990 to 2022 from the World Bank and the WHO, and employing estimation techniques such as Feasible Generalized Least Squares (FGSLS), Dynamic Fixed Effects (DFE), Double Least Squares (DMS), and quantile regression (QR), the results reveal that energy diversification reduces the infant mortality rate. Energy diversification significantly contributes to reducing infant mortality. Increasing the share of renewable energies, particularly solar and hydropower, improves access to stable electricity and reduces dependence on polluting fuels.
Keywords: Energy diversification, Child health, Sub-Saharan Africa, World Bank, WHO.

Introduction

Infant mortality remains one of the most alarming health challenges in sub-Saharan Africa. Although progress has been made in access to healthcare, the region continues to have some of the highest infant mortality rates in the world. According to UNICEF (2023), some rural areas still record up to 72 deaths per 1,000 live births, compared to a global average of 29. This excess mortality results from a complex web of structural factors: weak health infrastructure (Bado & Appunni, 2015), chronic underfunding of the health sector (Akazili et al., 2011), childhood malnutrition (Black et al., 2013), insufficient access to safe drinking water, and persistent exposure to preventable diseases such as malaria, pneumonia, and diarrheal infections (Liu et al., 2016). This situation reflects a chronic health crisis that is jeopardizing progress towards the Sustainable Development Goals (SDGs), particularly SDG 3 which aims to ensure a healthy life for all.

Furthermore, since the implementation of the Expanded Programme on Immunization, deaths of children under five have decreased significantly worldwide, from 12.5 million in 1990 to 5.2 million in 2020 (UNICEF, 2017). Globally, approximately 3 million child deaths are prevented each year through vaccination against diseases such as diphtheria, tetanus, pertussis, influenza, and measles. Conversely, vaccine-preventable diseases claim the lives of 8.8 million children under five each year. Sub-Saharan Africa and Central and South Asia account for approximately 80% of child deaths worldwide due to incomplete immunization coverage.

Beyond medical and institutional factors, environmental and energy-related factors have a major influence on children's survival. The widespread use of traditional fuels such as wood, charcoal, and kerosene for domestic needs remains common, particularly in peri-urban and rural areas. This energy dependence increases exposure to indoor air pollution, the leading cause of acute respiratory illnesses in children (WHO, 2022; Bonjour et al., 2013). The work of Smith et al. (2013) shows that prolonged inhalation of fine particulate matter from domestic combustion is closely linked to a significant increase in infant mortality. Similarly, Fullerton et al. (2008) highlight that indoor air pollution

kills more young children than HIV, malaria, or tuberculosis in several African countries. Despite this, public health policies still largely neglect this energy dimension, which is nevertheless central to preventing avoidable infant deaths.

In this context, energy diversification is emerging as a promising cross-cutting strategy for improving public health indicators, particularly those related to infant mortality. By facilitating access to modern, clean, and sustainable energy sources such as solar, hydroelectric, biogas, and wind power, the energy transition can significantly reduce dependence on traditional fuels and mitigate their harmful health effects (Sovacool et al., 2021; Jiménez et al., 2020). These energy alternatives have the potential not only to improve indoor air quality but also to ensure a stable power supply for healthcare facilities, thereby strengthening their resilience and capacity to respond (Pachauri et al., 2013; Rehfuess et al., 2014). In sub-Saharan Africa, several studies highlight the importance of integrating energy issues into health policies (Brew-Hammond, 2012; Kaygusuz, 2011). Rethinking access to energy through the lens of children's health is therefore not only an environmental necessity, but also a strategic response to the persistent challenges of human development.

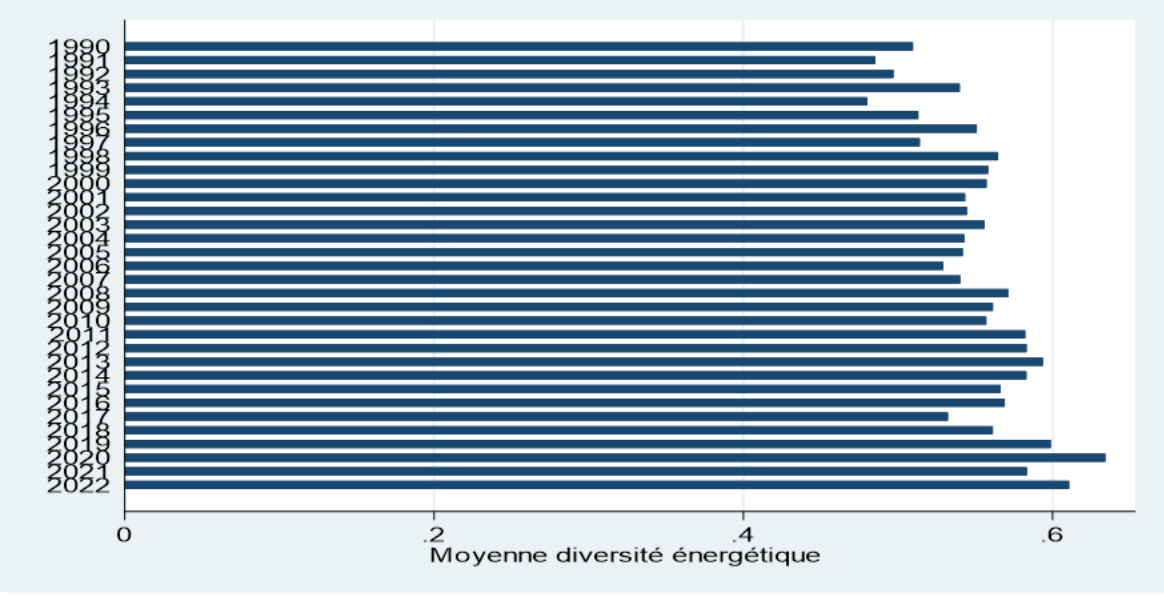
This research aims to inform public policy in sub-Saharan Africa, where infant mortality remains one of the most concerning health indicators. It is distinguished by its scope, covering a broad sample of countries in the region over the period 1990–2022. This temporal and spatial framework allows for the capture of the gradual transformations of African energy systems, marked by the increasing role of renewable energies. By adopting a comparative approach at the continental level, the study highlights regional disparities in the effects of energy diversity on children's health and underscores the importance of an energy transition tailored to local realities.

The objective of this work is to analyze the effect of energy diversification in Sub-Saharan Africa. To this end, the work will be structured around four main parts. Section (1.1) is devoted to the analysis of stylized facts, describing the evolution of infant mortality and the dynamics of energy diversification in Sub-Saharan Africa. It will highlight the main regional trends as well as the persistent disparities in access to modern energy sources. Section (1.2) presents a literature review, aiming to synthesize previous work on the interactions between energy policies, health conditions, and child health, while identifying the limitations of existing approaches. Section (1.3) is dedicated to the methodology: it specifies the nature of the data used, the variables of interest, and the econometric techniques employed. Finally, section (1.4) presents and discusses the results of the study.

1.1. Stylized facts

In this section, we present the evolution of energy diversity and child mortality in Africa between 1990 and 2023.

Figure 1.1: Evolution of energy diversity in Sub-Saharan Africa

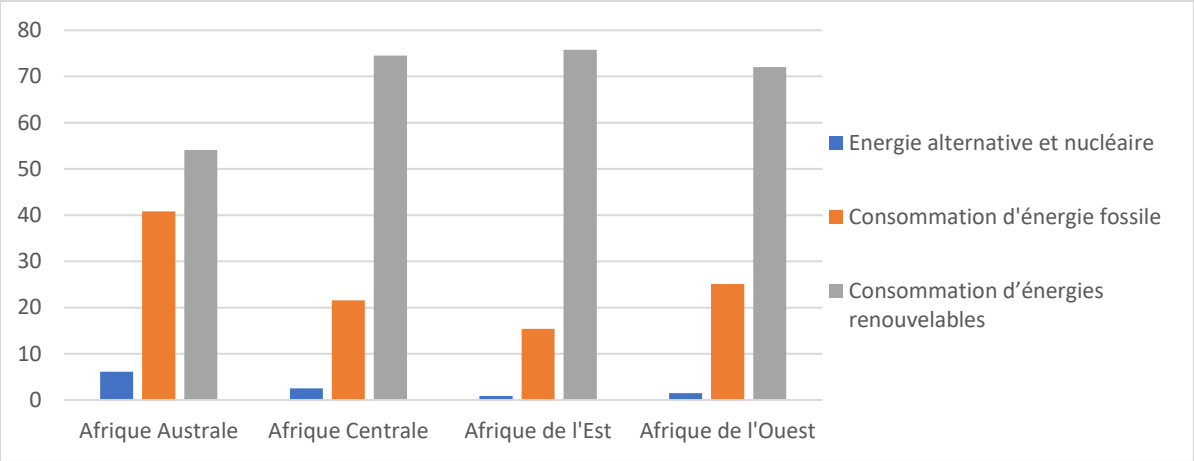


Source: author

Figure 1.1 illustrates the evolution of energy diversity in Sub-Saharan Africa between 1990 and 2022. Energy diversity, which reflects the distribution of energy sources in the energy mix, is a key indicator of the resilience and sustainability of energy systems.

Analysis of the graph shows that energy diversity in Sub-Saharan Africa remained relatively stable during the early decades, with limited variation between 1990 and the 2000s. However, from the 2010s onward, a slight upward trend is noticeable, suggesting a gradual diversification of energy sources. This trend can be attributed to increased adoption of renewable energies, such as solar and wind power, in response to energy transition policies and the need to reduce dependence on fossil fuels. Despite this progress, the evolution of energy diversity still exhibits fluctuations, which could indicate persistent challenges in integrating new energy sources. The variability observed after 2015 could be linked to factors such as investment instability, infrastructure constraints, or heterogeneous energy policies across African countries. By 2022, energy diversity had reached a relatively high level, suggesting progress toward a more balanced energy mix less reliant on conventional energy sources. Overall, this development reflects a gradual effort towards energy diversification in Africa, although challenges remain to ensure a sustainable energy transition and strengthen the continent's energy independence.

Figure 1.2: Energy Consumption in Sub-Saharan Africa

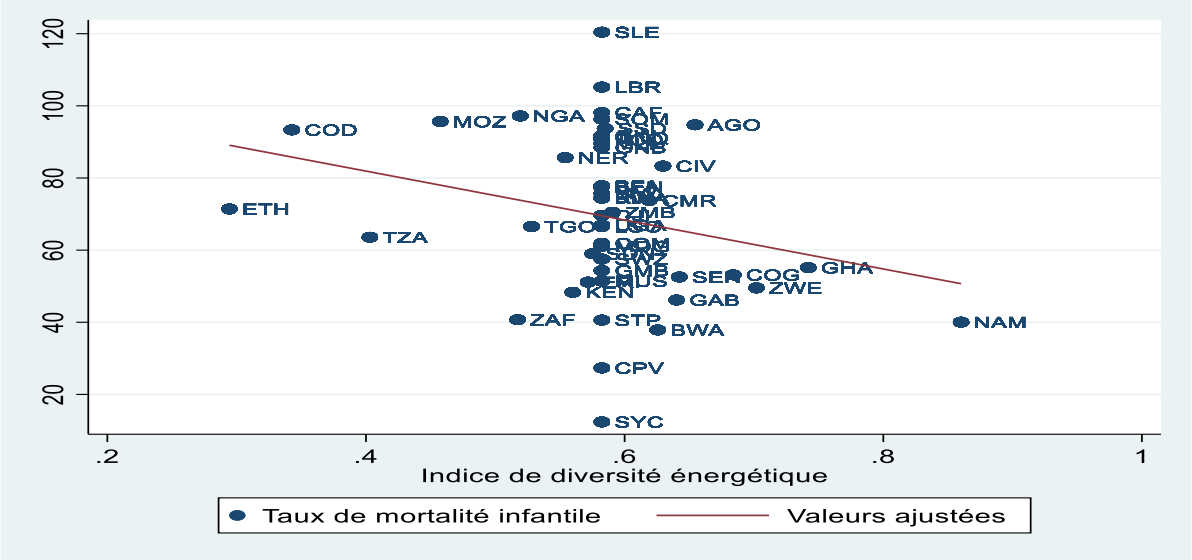


Source: author.

Energy consumption in sub-Saharan Africa is overwhelmingly based on renewable energy sources, as shown in Figure 1.2. In all the sub-regions studied (West Africa, East Africa, Central Africa, Southern Africa), more than 65% of the energy consumed comes from renewable sources, including traditional biomass, hydropower, and, to a lesser extent, solar power (International Energy Agency, 2022; World Bank, 2022). For example, East and West Africa have renewable energy consumption rates exceeding 70%. Conversely, the use of fossil fuels remains marginal, often accounting for less than 30% of total energy consumption. Alternative and nuclear energy is virtually non-existent (IEA, 2022). This energy profile reflects a strong dependence on local resources but also a low level of modernization in the energy sector (OECD, 2021). This situation presents opportunities for a green transition, but also exposes the country to risks of energy inefficiency.

Dependence on natural resources is also a major obstacle to economic diversification in sub-Saharan Africa. Figure 1.3 shows that Central Africa remains the most dependent on oil revenues, with 23.48% of GDP derived from this resource. Southern Africa follows with 20.38%, while East Africa (12.32%) and West Africa (10.09%) show lower levels. Revenues from forests are modest, ranging from 2.5% to 3.2% of GDP depending on the sub-region, while gains from natural gas remain marginal, with rates not exceeding 1.5%. This concentration around oil exposes these economies to the volatility of international markets. According to the Economic Commission for Africa (ECA, 2023), poor management of natural resources increases the economic vulnerability of the countries concerned. (Source: author based on World Bank, 2023).

Graphical link between energy diversity and child mortality in Sub-Saharan Africa



Source: author.

The graph illustrates the relationship between energy diversity and infant mortality rates in sub-Saharan Africa, suggesting that countries with a more diversified energy mix tend to have lower infant mortality rates. This observation is consistent with the work of Sovacool et al. (2012), which shows that diversifying energy sources reduces dependence on fossil fuels and promotes access to more stable electricity, which can improve the delivery of health services. Furthermore, the study by Rahut et al. (2020) highlights that access to clean energy reduces childhood respiratory illnesses, which are often exacerbated by the use of traditional biomass in households.

However, the wide dispersion of points reveals that the relationship is not uniform across countries, suggesting the influence of other structural factors such as the level of development, governance, and health infrastructure (González-Eguino, 2015). Furthermore, the study by Narayan et al. (2022) shows that the impact of energy diversity also depends on the quality of public policies regarding rural electrification and energy efficiency. Indeed, even with a more varied energy mix, the benefits for child health remain limited if access to electricity remains unequal or if health coverage is insufficient. Thus, this graph highlights the need for an integrated approach combining energy diversification, equitable access to electricity, and investments in health infrastructure to effectively reduce infant mortality in sub-Saharan Africa.

Literature review

Children's health is a fundamental pillar of human capital, a concept extensively developed by Becker (1964) and Schultz (1961). According to Grossman (1972), health is both a consumption good and an investment good: a healthy child will have better learning abilities, cognitive development, and future productivity. Heckman (2007) emphasizes the critical importance of the early years of life, highlighting that early health interventions strongly influence educational and economic trajectories. Strauss and Thomas (1995) remind us that health directly influences productivity through improved academic and professional performance. Ben-Porath's life-cycle theory (1967) also shows that initial health determines the future accumulation of skills. Thus, childhood health capital is recognized as a key determinant of educational and labor market returns (Currie, 2009). This approach is reinforced by the work of Cunha and Heckman (2007), who establish that complementary investments in health and education maximize the effects of one on the other, generating a virtuous cycle of development. Child health is therefore central to any sustainable human development strategy.

The theoretical literature highlights that disparities in childhood health are a major source of persistent social inequalities (Marmot, 2005; Currie, 2009). According to Galor and Zeira (1993), negative health shocks during childhood can exacerbate intergenerational income inequalities. Aghion and Howitt (1998) show that in an endogenous growth model, health influences not only the accumulation of human capital but also the innovative capacity of societies. According to Case and Paxson (2006), children in poor health exhibit lower cognitive

performance, resulting in reduced social mobility in adulthood. Bowles, Gintis, and Osborne (2001) also demonstrate that the intergenerational transmission of inequalities is partly mediated by health. According to Deaton (2003), investing in children's health effectively reduces poverty traps. This view is reinforced by Heckman's optimal investment model (2000), which specifies that returns on investment in health are higher when interventions occur early. Consequently, child health is a crucial lever for improving social mobility and reducing economic inequalities in the long term.

Child health plays a crucial role in economic growth processes, according to numerous theoretical studies. Barro (1996) demonstrates that health indicators, particularly infant mortality, are robust predictors of economic growth. Bloom, Canning, and Sevilla (2004) emphasize that improved health increases individual and national productivity. Lucas's growth model (1988) incorporates the quality of human capital, of which health is a key component, as a driver of endogenous growth. Weil (2007) argues that differences in living standards between countries can be partly explained by variations in population health from childhood onward. Furthermore, the "health-led growth" theory (Bhargava et al., 2001) considers child health as a driver of long-term GDP growth. Sachs (2001) highlights that in developing countries, poor child health is a major obstacle to sustainable growth. All of this work converges on the same idea: investing in children's health is an effective strategy to stimulate medium and long-term economic growth, by strengthening both productivity and innovation.

Human capital theory, formulated by Becker (1964) and inspired by the pioneering work of Schultz (1961), posits that health constitutes a strategic investment in increasing productivity and economic well-being. According to this approach, expenditures made to improve health are not simply costs but investments that generate returns in terms of longevity, efficiency, and income. From this perspective, children's health is crucial, as it shapes future trajectories of human and economic development. Infant mortality, as an indicator of poor early health, therefore reflects a significant loss of human capital. Grossman's work (1972) expanded this framework by emphasizing that health is also a durable good that individuals can accumulate, maintain, or degrade depending on their behavior and environment.

Applied to the energy context, human capital theory suggests that broader access to reliable and clean energy sources promotes investment in health (Becker, 1964; Grossman, 1972). In regions where energy diversity ensures a stable supply, health facilities improve the quality of care and reduce the risk of infant mortality (World Bank, 2020). Furthermore, according to Hutton and Rehfuess (2006), substituting polluting fuels with modern energy sources reduces the incidence of acute respiratory infections, a leading cause of infant mortality in many developing countries. At the household level, energy diversity influences children's health by freeing up time for caregiving (Duflo et al., 2008). Gathering firewood or using traditional fuels takes up valuable time, reducing attention to children (Pachauri & Jiang, 2008). When households have access to modern energy, parents, especially mothers, can devote more resources to children's education and health (Köhlin et al., 2011), thereby strengthening the accumulation of human capital from a young age.

In regions where energy diversity ensures a stable supply, healthcare facilities improve the quality of care and reduce the risk of infant mortality (World Bank, 2020). Furthermore, according to Hutton and Rehfuess (2006), replacing polluting fuels with modern energy sources reduces the incidence of acute respiratory infections, a leading cause of infant mortality in many developing countries. At the household level, energy diversity influences children's health by freeing up time for caregiving (Duflo et al., 2008). Gathering firewood or using traditional fuels takes up valuable time, reducing attention to children (Pachauri & Jiang, 2008). When households have access to modern energy, parents, particularly mothers, can dedicate more resources to children's education and health (Köhlin et al., 2011), thus strengthening the accumulation of human capital from an early age.

The environmental health approach, promoted by the World Health Organization (2006) and based on the work of McMichael (1999) and Prüss-Üstün and Corvalán (2006), considers the physical environment to be a major determinant of health. This perspective argues that polluted, unsanitary, and energy-insecure environments increase morbidity and mortality, particularly among children, who are more vulnerable to environmental risks. Unsanitary indoor air quality, poor water quality, and nutritional deficiencies caused by a degraded environment are among the leading causes of preventable infant mortality. This approach therefore calls for intervention not only at the medical level but also on the environmental determinants of health. In many regions, the traditional burning of biomass (wood, coal) for cooking and heating is a major source of indoor pollution. This exposure leads to respiratory infections, which are a leading cause of infant death. By introducing cleaner energy sources (gas, solar, renewable electricity), energy diversification reduces exposure to harmful particles and significantly improves indoor air quality.

Energy diversification plays a key role in reducing indoor pollution, a major cause of infant mortality according to Smith et al. (2014). The use of traditional biomass for cooking generates harmful particles that can lead to fatal respiratory illnesses (Bonjour et al., 2013). By introducing cleaner energy sources such as gas or solar power, families reduce children's exposure to these risks (Rehfuess et al., 2009), thus directly improving their survival. Energy diversity also improves the quality of health infrastructure (WHO, 2014). According to Adair-Rohani et al. (2013), the energy reliability of health centers is essential for equipment sterilization, vaccine storage, and neonatal care. In settings where multiple energy sources are available, interruptions to critical services are minimized (Bazilian et al., 2012), thereby contributing to a reduction in infant mortality.

Amartya Sen (1992) developed the capabilities approach to explain that human development should not be reduced to economic growth alone, but should be measured by individuals' actual ability to perform essential functions, such as living in good health. According to Sen, health is both an end in itself and a means of expanding life choices. Infant mortality constitutes an extreme deprivation of fundamental capabilities. Therefore, any improvement in the structural factors that affect health, such as energy, is essential to strengthening individual and collective freedoms. Access to energy diversity directly improves capabilities related to children's health. For example, reliable electricity enables access to quality health information through the media, facilitating vaccination and hygiene campaigns. Furthermore, diversified energy allows households to access water filtration technologies or clean cooking methods, reducing health risks. This contributes to providing children with better conditions for growth and reduces the risk of early mortality. Therefore, by strengthening energy diversity, we expand the fundamental freedoms of families to raise healthy children.

Energy diversification expands health capabilities by facilitating access to health services and information (Sen, 1992; Alkire, 2002). According to Lewis et al. (2013), access to electricity enables the dissemination of public health messages, supports vaccination, and improves household hygiene. Furthermore, the work of Hanna and Oliva (2015) shows that the use of clean energy reduces the risk of respiratory illnesses, allowing children to develop better. Energy diversity also promotes empowerment through education (Sen, 1999; Nussbaum, 2011). According to Khandker et al. (2014), electrifying schools improves access to health education for girls, the primary future mothers. Better education enables mothers to adopt preventive behaviors, positively influencing infant survival (Woldehanna et al., 2017).

Cherp and Jewell (2014) define energy security as the capacity of a system to withstand disruptions while ensuring affordable and sustainable access to energy services. This theory considers energy not only as an economic flow but also as a fundamental basis for social, economic, and health stability. The authors emphasize the importance of diversifying energy sources to reduce vulnerabilities. Excessive reliance on a single energy source exposes systems to shocks that can severely disrupt health services and compromise the safety of vulnerable groups, particularly children. A diverse energy supply ensures the continued operation of hospitals and clinics during crises. This is crucial to prevent disruptions in neonatal intensive care, vaccination, and the treatment of infectious diseases, which are leading causes of infant mortality.

Energy diversity increases the resilience of healthcare infrastructure to shocks (Cherp & Jewell, 2014). According to Sovacool (2011), having multiple energy sources reduces the risk of failures in hospitals, which are essential for neonatal care. In the event of natural disasters, the ability to power health centers from diverse resources saves lives (Ebinger & Vergara, 2011). Energy diversification also helps bridge the gap in access between urban and rural areas (Bazilian et al., 2012; Sovacool, 2012). According to Szabó et al. (2011), decentralized renewable energy systems can power remote health centers, thus giving rural children a better chance of survival. The development of mini-grids and off-grid solar solutions is a major lever for reducing infant mortality in isolated regions (Bhattacharyya, 2013).

Empirical review on the link between energy diversity and child health

Energy diversification is often seen as a lever for improving health outcomes, particularly infant mortality. Sarkodie and Strezov (2019), studying 54 African countries between 1990 and 2016 using generalized least squares (GLS), showed that diversification toward renewable energy significantly reduces infant mortality. Alvarez-Herranz et al. (2017), working on the European Union between 1995 and 2015 using dynamic panel data modeling (GMM), also found that greater energy diversity is correlated with better health indicators. Similarly, Chen et al. (2020), analyzing 30 Chinese provinces between 2000 and 2017 using fixed-effects models, confirmed that integrating clean energy reduces health risks associated with pollution, including infant mortality.

The literature also highlights the role of energy diversity in mitigating health shocks. Paramati et al. (2021), using a sample of 20 Southeast Asian countries between 1995 and 2018 and the Fully Modified Ordinary Least Squares

(FMOLS) method, show that energy diversification reduces health vulnerability in the event of environmental crises. Nourry (2015), analyzing 35 sub-Saharan African countries between 1990 and 2010 using static panel data models, reveals that access to a more varied energy mix is associated with a decrease in infant mortality, particularly by reducing the use of polluting energy sources. Furthermore, Omri and Nguyen (2014), through a panel of 15 countries in the Middle East and North Africa from 1990 to 2010, using the GMM panel methodology, conclude that energy diversification contributes indirectly to the improvement of public health.

Some research also highlights that energy diversification promotes healthier environmental conditions, thereby reducing infant mortality. Aslan and Apergis (2016), using data from 26 OECD countries between 1975 and 2012 with a panel cointegration approach, show that diversification towards renewable energies improves air quality and reduces child deaths. Rafiq and Salim (2012), based on a study of India between 1971 and 2008 using Autoregressive Distributed Lag (ARDL) techniques, confirm that diversified energy use reduces the negative health impact of pollution. Bildirici (2017), studying 14 developing countries between 1990 and 2013 using Toda-Yamamoto causality tests, finds that energy diversity leads to a direct decrease in infant mortality through the reduction of fine particulate matter emissions.

However, some studies highlight that energy diversification can produce heterogeneous effects across social groups. Sbia et al. (2017), examining 11 African countries between 1990 and 2015 using quantile panel data estimations, show that the beneficial impact of energy diversification on infant mortality is more pronounced in urban than in rural areas. Acheampong (2019), in his study of 43 African countries between 1990 and 2015 using the GMM system method, emphasizes that poor populations benefit less from energy diversity, thus limiting health gains. Furthermore, Jebli and Youssef (2017), through a study of 20 developing countries between 1995 and 2012 using panel cointegration, show that inequalities in access to clean energy limit the effects of energy diversity on health outcomes.

Other research indicates that the positive effects of energy diversification can be hampered by institutional failures. Omri et al. (2015), through a study of 17 Middle Eastern and North African countries between 1990 and 2012 using a panel ARDL approach, show that institutional inefficiency mitigates the health gains of energy diversity. Bayar and Gavriletea (2018), studying 27 European countries between 1995 and 2015 using dynamic panel models, find that without good governance, energy diversification does not significantly improve infant mortality. Rahman and Vu (2020), analyzing 23 Asian countries between 1990 and 2017 using the PMG (Pooled Mean Group) approach, confirm that the beneficial effect of energy diversity on health depends on the quality of public institutions.

Finally, some researchers further qualify the links, emphasizing that only diversification towards clean energy has significant positive effects. Shahbaz et al. (2017), in a study of 19 emerging countries between 1990 and 2014 using threshold cointegration, show that diversification still including fossil fuels does not significantly reduce infant mortality. Le et al. (2020), in a sample of 20 African countries between 1995 and 2015 using random-effects models, highlight that only diversification towards renewables positively influences health indicators. Apergis and Payne (2014), studying 80 countries from 1990 to 2010 using causality analysis, confirm that energy diversity dominated by fossil fuels does not generate any benefits in terms of infant health.

On the other hand, some authors argue that the effects of energy diversity on infant mortality may be limited in low-income countries. Al-Mulali and Sab (2018), studying 15 West African countries between 1990 and 2015 using the FMOLS method, found that the positive effects of diversification only materialize when income levels exceed a certain threshold. Ozturk (2017), using ARDL models on 29 developing countries between 1980 and 2010, shows that in contexts of extreme poverty, energy diversification does not lead to immediate gains in infant health. Balsalobre-Lorente et al. (2019), using a panel of 40 emerging countries between 1990 and 2016 via cointegration methods, confirm that the beneficial effect of diversification is contingent on levels of economic development.

Furthermore, several studies highlight non-linear effects. Destek (2020), studying 20 emerging economies between 1990 and 2017 using a quantile regression approach, finds that the effect of energy diversification on infant mortality is positive beyond a certain level of diversification. Nathaniel et al. (2021), analyzing 22 African countries between 1990 and 2020 using dynamic panel GMM, confirm that the relationship between energy diversity and infant health follows an inverted U-shaped curve. Kraft et al. (2015), studying 28 European countries between 1995 and 2012 using Panel Smooth Transition Regression (PSTR), find that the transition to high energy diversity is necessary to observe significant health effects.

Methodology

This section presents the analytical tools used to test the hypothesis that greater energy diversity contributes to reducing infant mortality in sub-Saharan Africa.

1.3.1. Theoretical and econometric models

This subsection presents the theoretical and econometric models used to analyze the effects of energy diversity on infant mortality.

1.3.2.1. Theoretical Model

The theory of environmental sustainability and health, formulated in the 1987 report of the World Commission on Environment and Development chaired by Gro Harlem Brundtland, highlights the direct link between environmental degradation and human health. The report, entitled "Our Common Future," defines sustainable development as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It emphasizes that the degradation of natural ecosystems, such as air and water pollution, biodiversity loss, and climate change, has direct repercussions on public health. Consequently, development strategies must integrate environmental preservation and the sustainable management of natural resources to ensure the health of future generations.

The report also highlights that the most vulnerable populations, often the poorest and living in densely populated areas, are the most exposed to environmental risks. These populations suffer not only from environmental degradation but also have limited access to healthcare. Social and environmental inequalities are thus inextricably linked. Indeed, increased pollution and the degradation of natural resources exacerbate health inequalities, with the most disadvantaged being the first to suffer. The central idea of this theory is that environmental sustainability and public health should not be seen as separate objectives but rather as interdependent.

One of the report's key concepts is that the sustainable use of natural resources, such as water, air, soil, and biodiversity, is essential for maintaining a healthy environment and, consequently, good public health. Overexploitation of natural resources and environmental pollution directly compromise the capacity of ecological systems to support human life. Therefore, natural resource management must become a priority to safeguard the long-term health of individuals and communities. The report emphasizes the importance of adopting sustainable resource management policies, including the protection of natural ecosystems that provide vital health services, such as air purification, drinking water supply, and climate regulation.

Furthermore, the theory of environmental sustainability and health also incorporates concerns related to climate change, which poses a growing threat to public health. Global warming leads to extreme events such as heat waves, floods, and droughts that disrupt access to water and food, while also creating new health risks, including vector-borne diseases. The report warns of the long-term effects of inaction on climate change, emphasizing that future generations could face major health challenges related to environmental disruptions.

To formalize the relationship between the environment, health, and development, a mathematical model can be used. An example of such a formalization could be a production function that depends on human capital, physical capital, and the environment, indicating that economic output (and therefore the well-being of populations) depends not only on traditional factors like labor and capital, but also on environmental quality. For example, a production function could be represented by:

$$Y(t) = A(t)H(t)^{\alpha}K(t)^{\beta}E(t)^{\gamma},$$

where $A(t)$ is a function of technology, $H(t)$ is human capital, $K(t)$ is physical capital, and $E(t)$ is environmental quality. This function shows that environmental quality (such as the absence of pollution and the preservation of ecosystems) is essential for optimal economic production, which, in turn, has a direct impact on the health and well-being of individuals.

Another aspect of formalization could be a welfare function $W(t)$ that integrates consumption, public health, and the environment. For example, the welfare function could be modeled as:

$$W(t) = C(t)^{\alpha}S(t)^{\beta}E(t)^{\gamma}$$

Where $C(t)$ represents the consumption of goods, $S(t)$ is an indicator of public health (e.g., the incidence of pollution-related diseases), and $E(t)$ is environmental quality. This mathematical model highlights the importance of health and the environment in maximizing human well-being, suggesting that policies promoting a healthy environment and sustainable resource management can significantly improve the quality of life for populations.

Thus, Brundtland's theory of environmental sustainability and health (1987) laid the foundations for a comprehensive approach to environmental and health management, emphasizing the importance of environmentally sound economic development to ensure the health of future generations.

1.3.2.2. Econometric Models

Based on the work of Hardy Zabatantou Louyindoula (2022) on the effects of public health spending on maternal mortality in CEMAC countries, our econometric model on the effect of energy diversity on infant mortality in Sub-Saharan Africa takes the form:

$$\text{Tau\_mort\_infantl} = f(Divers\_energ\_shannon, \text{Densite\_pop}, \text{Depens\_pub\_edu}, \text{Efficac\_gouvernc}, \text{PIB\_Tet}, \text{Ratio\_pop\_inact}, \text{Internet})$$

In general, the semi-logarithmic equation to be estimated is specified as follows:

$$\begin{aligned}\text{Tau\_mort\_infantl}_{it} &= \alpha + \beta_1 \text{Divers\_energ\_shannon}_{it} + \beta_2 \text{Densite\_pop}_{it} \\ &+ \beta_3 \text{Depens\_pub\_edu}_{it} + \beta_4 \text{Efficac\_gouvernc}_{it} + \beta_5 \text{PIB\_Tet}_{it} \\ &+ \beta_6 \text{Ratio\_pop\_inact}_{it} + \beta_7 \text{Internet}_{it} + \varepsilon_{it}\end{aligned}$$

With: Tau_mort_infantl, the infant mortality rate; Divers_energ_shannon, the Shannon energy diversity index; Densite_pop, the population density; Depens_pub_edu, public spending on education; Efficac_gouvernc, the governance efficiency; PIB_Tet, GDP per capita; Ratio_pop_inact, the ratio of the inactive population to the active population; Internet, the Internet user.

ε_{it} the error term of individual i at period t; $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6$ the coefficients of the explanatory variables for country i at period t; α the constant for individual i.

1.3.2. Presentation of study data and estimation techniques

This section describes the data used in the study and the estimation methods applied to analyze the link between energy diversity and infant mortality in sub-Saharan Africa. It specifies the data sources, the variables used, and the econometric techniques chosen to ensure reliable and relevant results.

1.3.2.1. Presentation of the study data

In this study, we analyze a panel of sub-Saharan African countries, selected due to their energy vulnerability and the challenges associated with accessing modern energy sources. The main objective is to assess how energy diversity contributes to reducing infant mortality. Indeed, broader and more diverse access to energy sources is seen as a key lever for improving health infrastructure, strengthening access to safe drinking water, ensuring better vaccine storage, and promoting safer living conditions, thereby reducing health risks for young children.

The analysis period spans from 1990 to 2022, as this period was marked by major reforms aimed at improving electrification, promoting renewable energy, and reducing dependence on fossil fuels. These reforms were accompanied by energy transition policies in a context where many countries sought to improve their health infrastructure and strengthen resilience to health crises. The data used come primarily from the World Development Indicators (WDI) and the World Health Organization (WHO), supplemented by regional sources for a more comprehensive assessment of the impact of energy diversity on infant mortality in sub-Saharan Africa.

The study uses the infant mortality rate as its dependent variable, measured by the number of deaths of children under one year of age per 1,000 live births. This indicator is fundamental for assessing the performance of health systems

and socio-economic conditions, reflecting health conditions, the level of development, and the effectiveness of public health policies in a country. (World Bank, 2022).

The variable of interest, energy diversity, is measured using the Shannon index, which captures the balanced distribution of energy sources. Greater energy diversity is associated with increased resilience of energy systems, promoting stable supply and access to energy, two crucial elements for strengthening health infrastructure and reducing infant mortality (Bazilian et *al* ., 2012).

The variable of interest, energy diversity, is measured by the Shannon index (Shannon, 1948), an indicator commonly used to quantify diversity in various fields, including ecology and energy economics. In an energy context, this index assesses the distribution of different energy sources in a country's total consumption. A high index indicates greater diversification of energy sources, thus reducing dependence on a single source and increasing the resilience of the energy system.

The Shannon index (H) is calculated as follows:

$$H = -\sum_{i=1}^{n} p_i \ln(p_i)$$

Where:

- p_i : Represents the share of each energy source in total energy consumption,
- $\ln(p_i)$: is the natural logarithm of this proportion,
- n: is the total number of energy sources considered.

In this study, the Shannon index is calculated taking into account three main energy sources:

- Alternative and nuclear energy (% of total energy consumption) includes nuclear energy and alternatives such as hydrogen. These energy sources are often seen as transitional solutions towards a more sustainable energy mix (Sadorsky, 2021).
- Fossil fuel consumption (% of total) includes oil, coal and natural gas, which remain dominant in many countries despite efforts to reduce their share (BP Energy Outlook, 2022).
- Renewable energy consumption (% of total final energy consumption) includes solar, wind, hydroelectric, and biomass energy. The growth of renewable energy is essential for the energy transition and the reduction of CO2 emissions (REN21, 2023).

Using these three categories allows us to assess energy diversity and measure dependence on fossil fuels or the progress of renewable energies. Several studies (Apergis and Payne, 2010; Bento and Moutinho, 2016) have shown that energy diversification is a key factor in economic resilience and environmental sustainability. By integrating these variables into the Shannon index, we obtain a synthetic measure of a country's energy diversification, essential for analyzing energy transition pathways.

A higher Shannon index indicates a better distribution of energy sources, which promotes a more stable power supply, essential for healthcare facilities and reducing the risks associated with infant mortality.

To control for contextual factors influencing infant mortality, several variables were included. (i) Population density was included to capture the effect of population pressure on health infrastructure and basic services, a key factor in highly urbanized countries (Bloom and Canning, 2003). (ii) Public spending on education was considered, as improving human capital promotes greater awareness of health practices and reduces the risks associated with infant mortality (Gakidou et *al*., 2010). (iii) Governance effectiveness was taken into account, as better management of public resources and the fight against corruption directly influence the quality of health services (Kaufmann et *al.*, 2011). (iv) GDP per capita was included as an indicator of the level of economic development, influencing households' ability to access healthcare and health infrastructure (Pritchett and Summers, 1996). (v) The ratio of the inactive population is included to capture the impact of demographic structure on infant mortality, as a larger working-age population is

often associated with better childcare (Bloom *et al.,* 2007). (vi) The internet usage rate is added as an indicator of digitalization, which plays an increasing role in disseminating health information and improving access to health services (Chinn and Fairlie, 2010).

Table (1) below presents the descriptive statistics of the variables used in the analysis of the effects of energy diversity on infant mortality in sub-Saharan Africa over the period 1990-2022.

Table 1 Descriptive statistics

Variable	Définitions	Obs	Mean	Std. Dev.	Min	Max
Tau_mort_infantl	Taux de mortalité infantile (pour 1 000 naissances vivantes)	1584	69.51	29.997	11.7	189.9
Divers_energ_shannon	Indice de diversité énergétique de Shannone	1584	.553	.211	-2.026	1.013
Densite_pop	Densité de la population (personnes par kilomètre carré de superficie des terres)	1584	75.733	89.534	1.663	545.678
Depens_pub_edu	Dépenses publiques en éducation (% du PIB)	1584	4.191	3.451	.127	75.628
Efficac_gouvernc	Efficacité de la gouvernance	1584	-.944	1.721	-38.438	1.02
PIB_Tet	PIB par habitant	1584	1683.765	2527.478	99.757	19849.718
Ratio_pop_inact	Ratio de la population inactive à la population active (% de la population en âge de travailler)	1584	87.195	12.943	43.165	115.888
Internet	Utilisateurs d'Internet (% de la population)	1584	8.188	14.231	0	81.593

Source: author.

The average infant mortality rate in the sample is 69.51 deaths per 1,000 live births, with a standard deviation of 29.997, reflecting wide variation among the countries studied. Minimum and maximum values range from 11.7 to 189.9, suggesting significant disparities in health conditions and access to child health services across countries. The Shannon index, measuring the diversification of countries' energy mixes, has an average of 0.553 with a standard deviation of 0.211. The average value indicates moderate diversity, but the index ranges from -2.026 to 1.013, showing that some countries are heavily dependent on one energy source, while others have a more balanced energy mix. The average population density is 75.733 people per km², with a standard deviation of 89.534. This suggests a wide variation in population density between countries, with some having very low densities (close to 1.66), while others are much more densely populated (up to 545,678). Public spending on education averages 4.191% of GDP, with a standard deviation of 3.451. These figures range from 0.127% to 75.628%, showing significant disparities in investment in education. This likely reflects differing national priorities regarding education funding.

The government effectiveness indicator has a mean of -0.944, suggesting significant governance challenges in the sample. The standard deviation of 1.721 and the extreme values ranging from -38.438 to 1.02 indicate marked variation in the quality of governance across countries, with some exhibiting very weak governance. The average GDP per capita is USD 1,683.77, with a standard deviation of USD 2,527.478, showing a large disparity between countries. The extreme values of USD 99.757 to USD 19,849.718 reveal significant disparities, with some countries having low GDP per capita while others are much wealthier. The average inactive population ratio is 87.195%, with a standard deviation of 12.943%, indicating that a significant proportion of the population in most countries is not actively engaged in the labor market. The values range from 43.165% to 115.888%, reflecting differences in demographic structure. Finally, the internet access rate averages 8.188% of the population, with a high standard deviation of 14.231%. This suggests significant disparities between countries, with some having almost no access, while others have relatively high rates (up to 81.593%).

Presentation of the estimation technique

Assessing the effects of energy diversity on infant mortality in sub-Saharan Africa requires a robust methodological approach to overcome the challenges inherent in this type of analysis, including heteroscedasticity, correlational errors, and endogeneity. The use of Feasible Generalized Least Squares (FGLS) is particularly relevant in this context. This method, widely used in time-series and panel data studies, corrects for heteroscedasticity and correlational errors in the data, thereby improving the accuracy of the estimates (Hsiao, 2014). Indeed, data series on energy diversity and infant mortality can exhibit unobserved variations that affect the results, rendering estimates using the OLS method unreliable. Furthermore, the FGLS method is suitable when more complex model specifications are required to account for the error structure in the data, thus enabling a better identification of the true effects of energy diversity on infant mortality.

The adoption of dynamic fixed effects (DFEs) is also essential for capturing unobserved time effects and country-specific variations. According to Arellano and Bond (1991), DFE models control for unobserved effects that are constant over time within countries, while also accounting for temporal changes that can affect outcomes. This method is particularly useful in contexts where variables of interest, such as energy diversity, have long-term effects that manifest gradually. For example, energy diversity can influence infant mortality through policies and infrastructure changes, but these effects are not instantaneous. By using dynamic fixed effects, it is possible to better isolate country- and time-specific variations, thus providing a more accurate estimate of the effects of energy diversity on infant mortality.

Quantile regression is another relevant approach for assessing the effects of energy diversity on infant mortality in sub-Saharan Africa, particularly when it is necessary to analyze how these effects vary across different parts of the infant mortality distribution. Indeed, the effects of energy diversity may not be uniform: some countries may have higher levels of infant mortality, while others experience relatively better conditions. Quantile regression, as proposed by Koenker and Hallock (2001), allows us to examine how the relationship between energy diversity and infant mortality differs at different quantiles of the mortality distribution. This approach is especially useful in contexts like sub-Saharan Africa, where disparities between countries are considerable. By allowing us to explore the effects in both low- and high-level infant mortality countries, quantile regression provides a more comprehensive picture of the impact of energy policies.

Finally, two-stage least squares (2SLS) is a fundamental technique for overcoming endogeneity problems in estimating the effects of energy diversity on infant mortality. Endogeneity problems arise when explanatory variables are correlated with the regression error, thus biasing the estimates. In the case of energy diversity and infant mortality, there may be unobserved common factors influencing both energy policy and health outcomes, such as similar economic or political conditions. Using 2SLS addresses this problem by introducing instrumental variables, such as energy diversity lags, to "clean" the causal relationships between the variables of interest (Angrist and Krueger, 2001). This ensures more robust and reliable results by reducing the potential bias related to the simultaneity and endogeneity of variables in the model.

The results of the tests performed justify the use of certain estimation techniques for this analysis. First, the collinearity tests, particularly the VIF, indicate that the independent variables do not exhibit excessive collinearity, with VIF values well below 10. This suggests that the variables can be included simultaneously in the model without introducing problematic multicollinearity, which is essential for obtaining reliable estimates. The Ramsey RESET test, with a high F-value and a probability of 0.0000, suggests that additional variables or transformations might be necessary to improve the model's specification. Thus, robust estimation techniques such as fixed-effects regression or generalized least squares (GLS) can be used to address specification and heteroscedasticity issues while still providing stable results.

The Breusch-Pagan test for heteroscedasticity, as well as the Ramsey RESET specification test, reveal problems with non-constant variance and incorrect specifications. According to White (1980) and Hausman (1978), such results can lead to biased estimates if classical statistical methods are used. These tests reinforce the idea that adjustments are necessary to prevent results from being skewed by model errors or unequal variance problems. Indeed, incorrect specifications can influence conclusions, as demonstrated by Wooldridge (2010), who highlighted the biases that can arise in the presence of heteroscedasticity and poor models.

1.4. Analysis and interpretation of results

In this section, we first present the results of the baseline analysis (1.4.1), followed by analyses of the link between energy diversity and infant mortality according to socioeconomic factors (1.4.2). Finally, we present the robustness analyses (1.4.3) to assess the reliability of the conclusions.

Baseline results

The results table below presents the effects of energy diversity on infant mortality in sub-Saharan Africa between 1990 and 2022 using the FGLS method.

Table 1 Baseline Results

	FGLS	FGLS	FGLS	FGLS	FGLS	FGLS	FGLS
	eq1	eq2	eq3	eq4	eq5	eq6	eq7
VARIABLES	Tau_mort_infantl	Tau_mort_infantl	Tau_mort_infantl	Tau_mort_infantl	Tau_mort_infantl	Tau_mort_infantl	Tau_mort_infantl
Divers_energ_shannon	-0.135***	-0.133***	-0.150***	-0.0451***	-0.0400***	-0.0501***	-0.0482***
	(0.0141)	(0.0140)	(0.0138)	(0.0156)	(0.0141)	(0.0127)	(0.0130)
Densite_pop		-0.114***	-0.117***	-0.152***	-0.179***	-0.175***	-0.176***
		(0.0176)	(0.0174)	(0.0174)	(0.0156)	(0.0138)	(0.0138)
Depens_pub_edu			-0.156***	-0.166***	-0.115***	-0.0455***	-0.0390**
			(0.0165)	(0.0162)	(0.0146)	(0.0147)	(0.0153)
Efficac_gouvernc				-0.243***	-0.202***	-0.166***	-0.173***
				(0.0159)	(0.0142)	(0.0128)	(0.0131)
PIB_Tet					-0.457***	-0.222***	-0.203***
					(0.0200)	(0.0214)	(0.0225)
Ratio_pop_inact						0.328***	0.311***
						(0.0201)	(0.0212)
Internet							-0.0423***
							(0.0143)
Constant	0.568***	0.597***	0.652***	0.737***	0.751***	0.484***	0.499***
	(0.00835)	(0.00899)	(0.00986)	(0.0110)	(0.0100)	(0.0195)	(0.0206)
Observations	1,584	1,584	1,584	1,584	1,584	1,584	1,584
Number of codespays	48	48	48	48	48	48	48

Source: author.

The results in the table on the effects of energy diversity (measured by the Shannon index) on infant mortality in sub-Saharan Africa show significant relationships across several model specifications. First, the energy diversity variable (Divers_energ_shannon) is consistently negatively correlated with infant mortality (Tau_mort_infantl) in all equations, indicating that greater energy diversity is associated with a reduction in infant mortality. This relationship is highly significant ($p<0.01$), and the effect size varies slightly across the specifications, ranging from -0.135 (equation 1) to -0.0400 (equation 5). These results suggest that improving the diversity of energy sources could have positive effects on child health, possibly through better access to energy and improved health infrastructure.

The inclusion of additional control variables reinforces this conclusion. Population density (Densite_pop) is also negatively correlated with infant mortality, which could reflect the effect of more targeted public policies in urban areas. The coefficient for Densite_pop ranges from -0.114 (Equation 2) to -0.176 (Equation 6), suggesting that more densely populated areas are generally associated with reduced infant mortality. This relationship is particularly strong in specifications that include other economic and social variables, indicating that more targeted health policies in these regions can be effective in reducing infant mortality. Furthermore, the dependence of public spending on education (Depens_pub_edu) shows beneficial effects on reducing infant mortality, with significant and negative coefficients in equations 3 to 5. The coefficients range from -0.156 (equation 3) to -0.0390 (equation 5), indicating that increased public spending on education is associated with a significant reduction in infant mortality, which could be the result of improved health education and better management of health services.

Governance-related variables, such as government effectiveness (Efficac_gouvernc), also play a key role in reducing infant mortality, with significant negative coefficients across all specifications. The coefficients for this variable range from -0.243 (Equation 3) to -0.166 (Equation 6), highlighting that more effective governments, capable of optimally managing public health resources, are associated with better child health. In parallel, GDP per capita (GDP_Tet) also shows a negative effect on infant mortality, with coefficients ranging from -0.457 (Equation 4) to -0.203 (Equation 7). This suggests that an increase in per capita income can indirectly improve child health, likely through better health infrastructure and a greater capacity to finance public health programs. Additional variables such as the inactive population ratio (Ratio_pop_inact) and internet access (Internet) also show significant effects. The ratio of the inactive population is positively associated with infant mortality, with coefficients of 0.328 (equation 6) and 0.311 (equation 7), suggesting that a high rate of inactivity in the economy may limit the resources available for healthcare, thereby increasing infant mortality. Internet access, on the other hand, has a significant negative effect on infant mortality, with a coefficient of -0.0423 in equation 7, which could reflect improved access to health information and services through digital platforms.

In summary, the results suggest that energy diversity plays a significant role in reducing infant mortality in sub-Saharan Africa. The findings in this table, which show a significant negative relationship between energy diversity and infant mortality, are consistent with several previous studies that have explored similar contexts in sub-Saharan Africa. For example, Akinbo et al. (2019) observed that access to more diversified energy in some parts of West Africa contributed to a reduction in infant mortality by facilitating improved living conditions and reducing illnesses related to poor air quality and inadequate sanitation. Tchatchouang et al. (2020), in a study in Central Africa, found similar results, highlighting that diversifying energy sources, such as renewable energy, improved sanitation infrastructure in rural areas, thereby contributing to a reduction in infant mortality. These results show that improved energy diversification not only enhances access to energy but also to healthcare services, a key factor in child health. Another important study by Balarabe et al. (2021) examined the impact of energy diversity in West and Central African countries and found that countries with greater energy diversity were better equipped to provide quality healthcare services and meet the energy needs of healthcare infrastructure, leading to a significant decrease in infant mortality. According to Balarabe et al.'s (2021) study, energy diversity not only improves access to modern healthcare services but also supports initiatives such as the electrification of healthcare facilities and the reduction of power outages, both essential conditions for children's health.

The objective of this study is to assess the effect of energy diversity on infant mortality in sub-Saharan Africa over the period 1990–2022. This period was marked by increasing efforts to diversify energy sources, particularly with a rise in the use of renewable energy. To ensure the robustness of the results, several econometric methods were employed: Feasible Generalized Least Squares (FGLS) to correct for heteroscedasticity, Dynamic Fixed Effects (DFE) to capture long-term effects, Quantile Regression (QR) to assess effects according to mortality levels, and Two-Party Least Squares (DPS) to address endogeneity issues. The main findings are as follows:

Energy diversification contributes significantly to reducing infant mortality. Increasing the share of renewable energies, particularly solar and hydropower, improves access to a stable electricity supply and reduces dependence on polluting fuels. This effect is particularly evident in countries that have implemented policies promoting the energy transition.

The impact of energy diversity varies across African sub-regions. The effects are more pronounced in Southern and East Africa, where hydropower plays a key role in electrifying households and healthcare infrastructure. Conversely, in Central and West Africa, where fossil fuels remain dominant and access to electricity is more limited, the effect of energy diversity on infant mortality is less significant.

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