PROBLEMY EKOROZWOJU/ PROBLEMS OF SUSTAINABLE DEVELOPMENT

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Energy Transition, Environmental Sustainability and Healthcare Costs in Emerging Sub-Saharan Economies: Evidence from the Pre- and During-COVID-19 Periods – Implications for SDG 3, SDG 7, and SDG 13

Transformacja energetyczna, zrównoważoność środowiskowa i koszty opieki zdrowotnej w rozwijających się gospodarkach Afryki Subsaharyjskiej: dowody z okresu przed pandemią i pandemii COVID-19 – implikacje dla Celów Zrównoważonego Rozwoju 3, 7 i 13

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Abstract

This study investigates the interconnections between energy transition, environmental sustainability, and healthcare costs in emerging Sub-Saharan African (SSA) economies, with a specific focus on their implications for Sustainable Development Goals (SDGs) 3 (Good Health and Well-being), 7 (Affordable and Clean Energy), and 13 (Climate Action). Employing a strongly balanced panel dataset of 40 SSA countries spanning 2005 to 2020, the analysis integrates Energy Transition Theory and Grossman's Health Production Model to evaluate how shifts in energy systems, environmental conditions, and healthcare financing affect sustainable development outcomes. Using panel estimation techniques, four interrelated econometric models examine the determinants of environmental sustainability, the impact of environmental quality and energy use on healthcare costs, the influence of health financing on outcomes, and the drivers of clean energy access. The results reveal significant regional disparities. Renewable energy consumption positively influences environmental sustainability in Central and East Africa but exhibits a negative effect in Southern Africa. GDP per capita is negatively associated with environmental quality across all regions, consistent with early-stage environmental Kuznets curve dynamics. Clean energy consumption is associated with lower healthcare expenditure, while public health spending has a more consistent positive effect on health outcomes than private spending. COVID-19 dynamics significantly altered these relationships. The pandemic weakened the previously strong link between renewable energy and environmental sustainability and intensified the negative association between GDP and environmental outcomes, particularly in West Africa. For healthcare outcomes, pre-pandemic patterns of effective public investment and economic growth were disrupted, as emergency responses and resource reallocation diluted long-term structural relationships. The contribution of GDP per capita to SDG 7 remained robust, even during the pandemic, reaffirming the foundational role of economic strength in driving energy transitions. However, the synergies between SDG 7 and SDG 13 weakened in most regions, with Southern Africa standing out for maintaining and even strengthening these interlinkages under crisis conditions. Demographic factors, such as population age, also exhibited regionally specific effects, particularly in Southern Africa, where they remained significant throughout the pandemic. These findings demonstrate the importance of regionally tailored and resilient policy strategies. Governments should prioritise clean energy investments, not only for environmental benefits but also to reduce healthcare burdens. Post-pandemic recovery plans must integrate green fiscal reforms and re-anchor health systems on principles of equity, resilience, and efficiency. The Southern African experience offers a potential blueprint for policy continuity and

SDG alignment during future crises. Overall, the research points to the need for coordinated, cross-sectoral interventions to accelerate sustainable development in Sub-Saharan Africa, particularly in the face of global shocks.

Key words: energy transition, environmental sustainability, healthcare expenditure, Sustainable Development Goals (SDGs), panel data analysis

Streszczenie

W niniejszym badaniu analizowane są powiązania między transformacją energetyczną, zrównoważonym rozwojem środowiska i kosztami opieki zdrowotnej w rozwijających się gospodarkach Afryki Subsaharyjskiej (SSA), ze szczególnym uwzględnieniem ich wpływu na Cele Zrównoważonego Rozwoju (SDGs) nr 3 (Dobre zdrowie i dobrostan), 7 (Przystępna i czysta energia) oraz 13 (Działania na rzecz klimatu). Wykorzystując silnie zbilansowany zestaw danych panelowych 40 krajów Afryki Subsaharyjskiej z lat 2005–2020, analiza integruje teorię transformacji energetycznej i model produkcji w ochronie zdrowia Grossmana, aby ocenić, jak zmiany w systemach energetycznych, warunkach środowiskowych i finansowaniu opieki zdrowotnej wpływają na wyniki zrównoważonego rozwoju. Wykorzystując techniki estymacji panelowej, cztery powiązane ze sobą modele ekonometryczne badają czynniki determinujące zrównoważony rozwój środowiska, wpływ jakości środowiska i zużycia energii na koszty opieki zdrowotnej, wpływ finansowania opieki zdrowotnej na wyniki oraz czynniki napędzające dostęp do czystej energii. Wyniki ujawniają znaczne różnice regionalne. Zużycie energii odnawialnej pozytywnie wpływa na zrównoważoność środowiskową w Afryce Środkowej i Wschodniej, ale negatywnie w Afryce Południowej. PKB na mieszkańca jest negatywnie skorelowany z jakością środowiska we wszystkich regionach, co jest zgodne z dynamiką krzywej Kuznetsa na wczesnym etapie rozwoju środowiska. Zużycie czystej energii wiąże się z niższymi wydatkami na opiekę zdrowotną, podczas gdy wydatki na zdrowie publiczne mają bardziej spójny pozytywny wpływ na wyniki zdrowotne niż wydatki prywatne. Dynamika COVID-19 znacząco zmieniła te zależności. Pandemia osłabiła wcześniej silny związek między energią odnawialną a zrównoważonością środowiska i nasiliła negatywny związek między PKB a wynikami środowiskowymi, szczególnie w Afryce Zachodniej. W przypadku wyników opieki zdrowotnej, wzorce efektywnych inwestycji publicznych i wzrostu gospodarczego sprzed pandemii zostały zakłócone, ponieważ reakcje kryzysowe i realokacja zasobów osłabiły długoterminowe zależności strukturalne. Wkład PKB na mieszkańca w realizację Celu Zrównoważonego Rozwoju nr 7 pozostał silny, nawet w czasie pandemii, potwierdzając fundamentalną rolę siły gospodarczej w napędzaniu transformacji energetycznej. Jednak synergia między Celami Zrównoważonego Rozwoju nr 7 a 13 osłabła w większości regionów, przy czym Afryka Południowa wyróżniała się utrzymaniem, a nawet wzmocnieniem tych powiązań w warunkach kryzysu. Czynniki demograficzne, takie jak wiek populacji, również wywierały wpływ specyficzny dla danego regionu, szczególnie w Afryce Południowej, gdzie utrzymywały się na wysokim poziomie przez cały okres pandemii. Odkrycia te dowodzą znaczenia strategii politycznych dostosowanych do specyfiki regionu i zapewniających odporność na zmiany. Rządy powinny priorytetowo traktować inwestycje w czystą energię, nie tylko ze względu na korzyści środowiskowe, ale także w celu zmniejszenia obciążeń systemu opieki zdrowotnej. Plany odbudowy po pandemii muszą uwzględniać zielone reformy fiskalne i ponownie zakotwiczyć systemy opieki zdrowotnej w oparciu o zasady równości, odporności i efektywności. Doświadczenia Afryki Południowej stanowią potencjalny wzór dla ciągłości polityki i dostosowania do Celów Zrównoważonego Rozwoju (SDGs) w przypadku przyszłych kryzysów. Podsumowując, badania wskazują na potrzebę skoordynowanych, międzysektorowych interwencji w celu przyspieszenia zrównoważonego rozwoju w Afryce Subsaharyjskiej, szczególnie w obliczu globalnych wstrząsów.

Słowa kluczowe: transformacja energetyczna, zrównoważoność środowiskowa, wydatki na opiekę zdrowotną, Cele Zrównoważonego Rozwoju (SDG), analiza danych panelowych

1. Introduction

The pursuit of sustainable development in Sub-Saharan Africa (SSA) is increasingly constrained by a confluence of structural challenges relating to energy poverty, environmental degradation, and deteriorating public health outcomes. These challenges persist amidst mounting global commitments to the Sustainable Development Goals (SDGs), particularly SDG-3 (Good Health and Well-being), SDG-7 (Affordable and Clean Energy), and SDG-13 (Climate Action). In a region where nearly 600 million people lack access to electricity (Tomala et al., 2021) and where health systems are frequently under-resourced and overstretched, understanding the interlinkages among energy transition, environmental sustainability, and healthcare costs is critical to informing holistic and effective policy responses.

While the global discourse on sustainability has largely shifted towards integrated development models, the empirical exploration of these interdependencies in the African context remains limited. Previous studies have shown that increased access to renewable energy can foster productivity gains and enhance environmental performance

(Diallo, 2024; Lin & Sai, 2022), yet the implications for health system financing and outcomes are less well understood. Furthermore, existing literature suggests that clean energy transitions may reduce exposure to pollutants and alleviate environmentally driven disease burdens (Adhvaryu et al., 2023), but empirical validation of these relationships within SSA economies is still emerging. Similarly, environmental degradation – manifested through deforestation, greenhouse gas emissions, and water and air pollution – has been linked to increased healthcare costs and adverse health outcomes (Parise, 2018; Usman et al., 2019), underscoring the pressing need to consider environmental quality as a determinant of health expenditure.

The theoretical underpinnings of this study draw from Energy Transition Theory and Grossman's Health Production Model. The former posits that a structural shift from fossil fuels to renewable energy sources generates environmental and socio-economic dividends, while the latter conceptualises health as a form of capital influenced by healthcare inputs and environmental conditions (Grossman, 1972; adapted in Boachie et al., 2018). These frameworks collectively offer a useful lens through which to assess how clean energy adoption influences environmental sustainability and, in turn, shapes health system costs and public health outcomes.

Despite this conceptual clarity, a critical gap persists in the literature regarding the empirical examination of the nexus between energy systems, environmental sustainability, and healthcare financing in SSA. Most extant studies adopt siloed approaches, treating energy, environment, and health as discrete domains rather than components of a dynamic and interdependent system (Müller et al., 2021; Stevenson et al., 2021). Consequently, the synergies and trade-offs among the relevant SDGs remain underexplored in empirical terms, especially in low- and middle-income countries (Niet et al., 2020; Onabola et al., 2022). Moreover, existing empirical models rarely capture the compounded effects of energy transition on both environmental quality and public health financing, thereby limiting the evidence base required for effective policy formulation. Studies have highlighted the critical role of clean energy adoption (Luan et al., 2025; Mohamed et al., 2024), renewable technologies (Imandojemu et al., 2025), and green fiscal policies (Yin et al., 2022) in achieving carbon neutrality. Other studies emphasise how energy use, economic growth, and institutional factors influence emissions and environmental performance (Adeleye et al., 2021; Osabohien et al., 2024). The contributions also underscore gender policy impacts (Abd Majid et al., 2025) and global value chains (Osabohien et al., 2024) as vital for sustainability transitions.

Cai, Xiang, and Akbari (2025) propose a comprehensive sustainability perspective that links circular economy, environmental development, and social equity through sustainable development spillovers. This directly supports the manuscript's systems-based approach, which emphasizes that energy, environment, and health outcomes are not isolated domains but are closely interconnected and require integrated policy strategies. Li et al. (2024) examine how COVID-19 infection following embryo transfer affects early pregnancy outcomes. Although situated in a clinical context, their findings underscore the broader theme shared with the manuscript: that pandemic shocks can significantly disrupt health outcomes and systems. The manuscript extends this idea by showing how COVID-19 altered energy-environment-health linkages in SSA, weakening prior synergies and reshaping the effectiveness ofpublic health spending and energy use.

Wang et al. (2024) highlight the disparities in healthcare-seeking behavior between impoverished and non-impoverished groups, revealing systemic inequality in access to care. This aligns with the manuscript's findings that in SSA, public health investments are more consistently linked to improved outcomes than private expenditure, particularly in vulnerable and rural populations. Both studies advocate for health policy that is equitable and inclusive. Li et al. (2021) explore behavioral shifts during the COVID-19 pandemic, specifically changes in smartphone usage. Their study, while technology-focused, reinforces the idea that global crises profoundly impact social behavior – a theme the manuscript echoes in showing how energy use patterns and health financing shifted during the pandemic, particularly in the face of lockdowns and resource reallocation. Wang, Jiang, Yang, and Pan (2022) investigate the burden of travel for medical care and its determinants. Their findings parallel the manuscript's assertion that in SSA, limited infrastructure and regional disparities significantly increase healthcare access barriers and costs. Both studies point to the importance of addressing infrastructural constraints in promoting equitable health outcomes.

This study addresses this gap by examining the triadic relationship between energy transition, environmental sustainability, and healthcare costs in emerging SSA economies. Specifically, it assesses how clean energy access affects environmental quality; how environmental degradation influences healthcare expenditure; and how health system financing interacts with environmental and energy variables to shape health outcomes. To this end, the study develops a suite of econometric models informed by Energy Transition Theory and the Health Production Model, using a panel of SSA countries to empirically estimate the effects of renewable energy adoption, natural resource depletion, healthcare spending, and macroeconomic indicators on key sustainability and health metrics.

By providing new empirical insights into the interdependencies among SDG-3, SDG-7, and SDG-13, this research contributes to a more integrated understanding of sustainable development in SSA. It advances the literature on the health-energy-environment nexus and offers a policy-relevant framework for designing interventions that simultaneously target climate resilience, energy equity, and health system efficiency in resource-constrained settings.

2. Literature review

2.1. Energy transition in Sub-Saharan Africa

The energy transition in Sub-Saharan Africa (SSA) is shaped by structural constraints and development imperatives, alongside the global push for decarbonisation. While there has been gradual progress towards cleaner energy, energy poverty remains pervasive. Diallo (2024) finds that renewable energy shares above 32.63% significantly boost green productivity and fosters long-term convergence. Financial development is a key enabler of this transition, particularly in low-income countries, by improving access to clean energy finance (Mugume & Bulime, 2024). Lin and Sai (2022) further attribute improvements in energy productivity to technological advancement and GDP growth, although with notable inequalities across income groups.

Renewable energy access is central to achieving Sustainable Development Goal 7 (SDG-7). Integrated policies on access, efficiency, and renewables can reduce emissions and lower investment needs (Dagnachew et al., 2020). Haldar et al. (2023) underscore the importance of governance and public spending in expanding renewables and reducing energy poverty. However, Müller et al. (2021) stress the need to incorporate energy justice principles to avoid trade-offs and enhance co-benefits, particularly in underserved communities.

Despite progress, SSA faces persistent barriers to energy transition. Inadequate infrastructure, outdated equipment, and poor maintenance limit power adequacy (Ebhota, 2021). Financing remains a major constraint, with renewable energy (RE) and energy efficiency (EE) investment potential largely untapped due to institutional and policy deficiencies (Mungai et al., 2021). Daggash and Mac Dowell (2021) note that SSA's limited financial and technical resources hinder the scaling of clean energy, while fossil fuels still play a transitional role. Tomala et al. (2021) add that rapid population growth and climate change further complicate the region's energy outlook.

The energy transition's impact on poverty and inclusivity is context-specific. Although low-carbon energy systems can enhance access and affordability, rural-urban disparities persist. Emodi et al. (2022) show that energy choices are influenced by income, education, household size, and internet access, with rural households more sensitive to price changes. Global evidence presents mixed outcomes: in China, clean transitions have alleviated energy poverty (Dong et al., 2021), while in Poland, rising heating costs worsened it (Karpinska & Śmiech, 2021). The multidimensional nature of energy poverty, shaped by global crises and domestic conditions, calls for equity-focused approaches (Štreimikienė & Kyriakopoulos, 2023; Jones & Reyes, 2023).

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2.3. Healthcare costs and public health outcomes – literature review

The relationship between healthcare expenditure and public health outcomes is well-established across both developed and emerging economies, with increasing attention to the role of environmental determinants in shaping health system burdens and effectiveness. In regions such as SAARC-ASEAN and sub-Saharan Africa (SSA), studies demonstrate that rising public and private health investments correlate with reduced infant mortality and crude death rates (Rahman et al., 2018; Boachie et al., 2018). In Ghana, for instance, a 10% increase in public health expenditure was found to avert 4.4 infant deaths per 1,000 live births and modestly improve life expectancy (Boachie et al., 2018), although income growth remained a more potent determinant. Similar patterns are evident in high-income settings; in Australia, increased public health spending led to significant reductions in Years of Life Lost, particularly in underserved areas (Edney et al., 2018). These findings underscore the importance of economic and fiscal policy frameworks in shaping health system responsiveness, particularly in emerging economies where revenue mobilisation and labour market participation influence healthcare financing (Zhou et al., 2020).

However, the positive impacts of healthcare investment are increasingly offset by environmental stressors, particularly those linked to fossil fuel dependency. The health consequences of air pollution—chiefly from fossil fuel combustion – are profound, with PM2.5 exposure alone responsible for an estimated 6.81 million premature deaths globally each year (Schwartz et al., 2019). Empirical evidence from Colombia shows that regions with intensified thermal energy production experience heightened pollution levels and a consequent 56% rise in cardiovascular-related emergency mortality, alongside a 9% increase in respiratory-related morbidity (Adhvaryu et al., 2023). These outcomes highlight the intersection of energy policy and public health, revealing how the carbon intensity of development – measured through the Carbon Intensity of Well-Being (CIWB)—can compromise both social and environmental sustainability (Thombs, 2022). In SSA, where fossil fuel reliance intersects with weak environmental regulation and limited healthcare infrastructure, the health implications of environmental degradation are likely to be especially severe.

Climate change, driven primarily by fossil fuel emissions, further intensifies health vulnerabilities. Rising temperatures, extreme weather events, and shifts in disease vectors contribute to a growing burden of both communicable and non-communicable diseases (Parise, 2018). These risks disproportionately affect populations in tropical and low-income settings, underscoring the urgency of targeted mitigation and adaptation strategies under Sustainable Development Goal 13 (SDG-13). Yet the capacity to implement such strategies remains constrained by limited institutional resources and competing developmental priorities. The economic burden of environmentally mediated diseases is escalating in many emerging economies, with chronic conditions like type 2 diabetes imposing billions in direct and indirect costs (Anstee et al., 2019). Air pollution, proxied by CO_2 emissions, has been shown to increase government healthcare expenditures while reducing private health investment, suggesting asymmetric burdens across income groups (Usman et al., 2019). Furthermore, greenhouse gas emissions have been directly linked to increased incidence of climate-sensitive diseases such as malaria, while economic growth and public health spending can help mitigate these effects (Wei et al., 2022).

Quantifying the full extent of environmental impacts on health systems remains methodologically challenging. The Global Burden of Disease framework has attempted to fill critical data gaps, particularly in estimating risks associated with pollutants and climate change (Shaffer et al., 2019). However, limited exposure-risk data and the exclusion of subclinical effects, such as those from neurotoxicants like lead, undermine the accuracy of current models. Addressing these limitations is essential for designing effective, cost-efficient prevention strategies and for guiding health policy in resource-constrained settings.

Efforts to achieve Sustainable Development Goal 3 (SDG-3)—ensuring healthy lives and promoting well-being for all must therefore extend beyond direct healthcare interventions to include environmental and infrastructural determinants. While health spending has demonstrable effects on reducing maternal and infant mortality (Owusu et al., 2021), challenges such as catastrophic health expenditure (CHE), particularly among rural and female-led households, remain widespread (Sayuti & Sukeri, 2022). Accessibility also varies significantly, influenced by transport networks and socioeconomic status (Korah et al., 2023). As Acharya et al. (2018) argue, health system strengthening must account for environmental risks and structural inequalities. Progress towards universal health coverage and SDG-3 will thus depend not only on scaling financial protection mechanisms and healthcare provision but also on aligning climate, energy, and health policies to mitigate environmental risks that increasingly shape public health outcomes.

2.4. Interlinkages between energy, environment, and health – literature review

The interplay between energy systems, environmental sustainability, and public health has emerged as a focal point in global sustainable development discourse, particularly as it relates to the achievement of Sustainable Development Goals (SDGs) 3 (Good Health and Well-being), 7 (Affordable and Clean Energy), and 13 (Climate Action). These goals are not only interdependent but also generate synergies and trade-offs that influence the efficacy of policy interventions. Cerf (2019) and Onabola et al. (2022) emphasise the critical need to adopt integrated frameworks that reflect the interconnectedness of these domains, particularly through the lens of equity and inclusivity. Building on this, Stevenson et al. (2021) argue that climate action policies often overlap with goals focused on clean energy and sustainable urbanisation, underscoring the importance of cross-sectoral coordination in identifying co-benefits and managing policy trade-offs. Similarly, Niet et al. (2020) advocate for expanding

traditional nexus frameworks to explicitly incorporate health, ecological diversity, and economic well-being, thus facilitating more coherent policymaking across the 17 SDGs.
The empirical literature reinforces these conceptual linkages by demonstrating how transitions to clean and renewable energy sources can simultaneously advance climate mitigation and improve health outcomes. Markandya et al., (2018) estimate that air pollution reductions stemming from cleaner energy sources can yield health benefits that, in some cases, exceed the costs of climate mitigation. Iacobuță et al. (2021) further illustrate that improvements in energy efficiency and renewable deployment generate multiple co-benefits for climate and health, suggesting a strong rationale for prioritising such transitions in policy design. In the context of China, Li et al. (2023) find that clean residential heating has led to improved public health outcomes, with health gains outweighing energy costs in several provinces, although these gains are uneven and contingent on income levels, pointing to the need for targeted support. Pereira et al. (2021), however, caution that historical energy transitions have sometimes yielded mixed results, contributing to both declining mortality and increases in chronic, pollution-related diseases, thereby highlighting the need for context-specific approaches.
The health implications of environmental sustainability are also increasingly evident in the healthcare sector itself. Hospitals and health services adopting green practices not only reduce emissions but also improve operational efficiency and patient care quality. Han et al. (2024) find that environmentally responsible practices in healthcare facilities positively affect service quality and financial outcomes. Similarly, Benedetto et al. (2024) show that mobile cancer screening units in rural Italy not only lower travel-related emissions but also reduce economic burdens such as productivity losses. Zanobini et al. (2024) expand this argument by linking health literacy to reduced environmental and financial healthcare burdens, suggesting that informed populations can play a significant role in supporting sustainable healthcare systems. Hughes et al. (2022) reinforce the urgency of these interventions by estimating that the healthcare sector contributes between 1% and 5% of global greenhouse gas emissions, thus making environmental sustainability in healthcare an essential component of broader climate action strategies.
The integration of health into energy and environmental policy is further supported by studies calling for the expansion of the traditional Water-Energy-Food nexus to include health as a critical dimension (Nuwayhid & Mohtar, 2022). This broader approach is validated by evidence from energy-insecure settings, where inadequate access to clean energy correlates with reduced water, sanitation, and negative health outcomes (Katekar et al., 2020). Moreover, Jiang et al. (2021) argue for a more nuanced healthcare-energy-environment nexus in the wake of the COVID-19 pandemic, pointing to systemic vulnerabilities and the need for holistic, cross-sectoral policy responses. Reames et al. (2021) also highlight the role of household energy burden, environmental quality, and social capital in shaping health outcomes, thereby reinforcing the interconnected nature of energy justice, environmental quality, and public health.
In summary, the interlinkages between energy, environment, and health are central to achieving the SDGs, with clean energy transitions offering substantial co-benefits for both health and climate resilience. These linkages necessitate integrated planning and policy approaches that transcend traditional sectoral boundaries. Promoting environmental sustainability not only enhances health outcomes but also contributes to the reduction of healthcare costs and the creation of more resilient health systems. The empirical evidence makes clear that sustainable energy transitions are not merely technological or economic shifts – they are foundational to improving human well-being and ecological integrity in tandem.

2.5. Empirical review

This empirical review synthesises recent scholarly contributions on the nexus of environmental sustainability, energy transitions, public health, and socioeconomic inequalities, with a focus on emerging and developing economies. Employing diverse methodologies – from econometric modelling and policy mapping to systems analysis and household surveys. These studies provide comprehensive insights into how intertwined environmental and economic dynamics influence sustainable development outcomes.
Several studies address the intersection of environmental degradation, economic growth, and public health expenditure. Usman et al. (2019) conduct a panel data analysis of 13 emerging economies, revealing a bifurcated impact of environmental pollution: CO_2 emissions and environmental deterioration increase government health spending but decrease private expenditures. GDP growth positively affects both public and private health outlays, while foreign direct investment has an asymmetric influence. Other non-economic variables, such as population ageing, elevate health costs, whereas higher secondary education mitigates private health spending. These nuanced relationships highlight the complex role of environmental and socioeconomic factors in shaping health financing.
Closely linked to the public health dimension, Sayuti and Sukeri (2022) examine catastrophic health expenditure (CHE) in Malaysia using household-level data. Their findings show that 2.8% of households faced CHE, with vulnerable groups including female-headed and rural households. Although relatively low in prevalence, the increasing trend signals a need for more inclusive and protective health financing systems. Complementing these insights, Zanobini et al. explore health literacy as a critical element of healthcare sustainability. They argue that health literacy can reduce disparities, cut costs, and improve environmental outcomes, advocating for reforms that embed literacy into health systems to enhance both individual and systemic resilience.

Energy transitions emerge as a central theme in the literature, particularly in the context of Africa. Müller et al. (2021) analyse renewable energy policies across 34 African countries through the lens of energy justice. They identify four typologies of justice integration and critique the SDG framework's failure to adequately address procedural, distributive, and recognitional justice. Their work highlights the importance of embedding equity and justice into energy policymaking to ensure broader social acceptance and sustainability.

Furthering the discourse on renewable energy, Mugume and Bulime (2024) investigate how financial development supports clean energy adoption in 20 sub-Saharan African countries. Their econometric analysis shows that financial institutions, not markets, are the primary drivers of renewable energy uptake, especially in low-income contexts. The study recommends innovative financial tools such as green bonds and digital finance to enhance private investment in the region. Similarly, Agoundedemba et al. (2023) provide a regional analysis of Africa's renewable energy landscape, identifying disparities in electrification and technological uptake. They stress the need for robust infrastructure, policy coherence, and targeted investment to unlock the continent's vast renewable potential.

From a systems perspective, Daggash et al. examine the pathways to sustainable power in Nigeria and SSA. Using systems modelling, they show that climate commitments under the Paris Agreement can be met without prohibitive costs. However, the intermittency of renewables necessitates a complementary role for fossil fuels in the short term. Decentralised renewable systems, while more expensive, offer democratic dividends such as job creation and equitable development, underscoring the need for balanced energy strategies that are both climate-aligned and socially inclusive.

Streimikiene et al. provide a comprehensive literature review on energy poverty, particularly as it relates to the global shift toward low-carbon energy systems. They underscore the socio-political factors like COVID-19 and the Russo-Ukrainian war that exacerbate household vulnerability, especially in the global South. Their work calls for socially sensitive energy policies that do not sacrifice equity for environmental goals.

Finally, Reames et al. (2021) offer insights from a developed economy context, analysing U.S. county-level data to link household energy burden, social capital, and environmental quality with public health outcomes. Their findings show that high energy burdens correlate with poor health indicators, including premature mortality and reduced life expectancy. This interdependence of energy, environment, and health underscores the value of integrated policy interventions.

Across these diverse empirical investigations, a common thread emerges: sustainable development is inherently multidimensional, demanding frameworks that integrate economic viability, environmental stewardship, and social equity. Whether it is through health expenditures shaped by pollution and demographic shifts, or energy transitions driven by justice and financial innovation, the studies reviewed herein illuminate the complexity and interdependence of global development challenges. Together, they call for targeted, context-specific, and interdisciplinary policy responses to foster resilience and sustainability in an increasingly volatile global landscape.

3. Methodology and theoretical framework

This study draws upon two complementary theoretical frameworks: Energy Transition Theory and Grossman's Health Production Model, to structure its empirical investigation into the interconnected dynamics of energy use, environmental quality, healthcare costs, and health outcomes in Sub-Saharan Africa (SSA).

Energy Transition Theory posits that a shift from fossil-based to renewable and sustainable energy sources leads to improved environmental quality, reduced carbon emissions, and long-term socio-economic gains. In this context, clean energy adoption is expected to enhance environmental sustainability (SDG 13) while simultaneously promoting access to affordable and reliable energy (SDG 7). These environmental improvements, in turn, are presumed to yield positive externalities for public health, including reduced exposure to pollution-related illnesses and improved living conditions. Grossman's Health Production Model views health as a form of capital produced through various inputs, such as medical care, lifestyle, and environmental quality. Within this framework, environmental conditions, shaped by energy choices and sustainability policies, serve as crucial determinants of both health outcomes and healthcare expenditure. Thus, environmental degradation increases the demand for healthcare services and raises associated costs, whereas improved environmental sustainability, potentially fostered by energy transitions, contributes to better health and reduced financial burden on health systems (SDG 3).

Bridging these theoretical foundations with empirical inquiry, the study develops four models that operationalize the conceptual relationships implied by both frameworks. Specifically, the models examine: (i) the determinants of environmental sustainability; (ii) the effects of environmental quality on healthcare expenditure; (iii) the impact of health financing on health outcomes; and (iv) the drivers of clean energy access and use. The selection of variables, including renewable energy consumption, natural resource depletion, healthcare expenditure (public and private), GDP per capita, and demographic characteristics, is thus directly informed by these theoretical perspectives.

Accordingly, the empirical strategy models key sustainable development outcomes (SDG-3, SDG-7, and SDG-13) as functions of energy transition indicators, environmental sustainability measures, health cost variables, and socioeconomic controls. This alignment ensures theoretical coherence while enabling a robust evaluation of the interdependencies between energy policy, environmental outcomes, and public health in emerging SSA economies.

3.1. Variable description

This study uses a strongly balanced panel dataset comprising 40 SSA countries selected across four regions:
Central Africa – Angola, Cameroon, Central African Republic, Congo, Dem. Rep., Congo, Rep., Gabon, and Sao Tome and Principe.
East Africa: Burundi, Comoros, Ethiopia, Kenya, Madagascar, Malawi, Mauritius, Mozambique, Rwanda, Tanzania, Uganda, and Zambia.
Southern Africa: Botswana, Eswatini, Lesotho, Namibia, South Africa.
West Africa: Benin, Burkina Faso, Cabo Verde, Cote d'Ivoire, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Togo.

Table 1. Variables description, expectations, and sources, source: Authors' compilation

Variable	Description	Model 1	Model 2	Model 3	Model 4	Expected Relationship
SDG 3	Good Health and Well-Being	N/A	N/A	N/A	N/A	N/A
SDG 7	Affordable and Clean Energy	N/A	N/A	N/A	N/A	N/A
SDG13	environmental sustainability (Climate Action)	N/A	– Negative	N/A	+ Positive	Improved environmental quality lowers health costs and may encourage renewable energy transitions
REC	Renewable energy consumption (% of total final energy consumption)	+ Positive	– Negative	N/A	N/A	Higher renewable use improves environmental sustainability and reduces health costs.
GDPC	GDP per capita (constant 2015 US$)	+ Positive	– Negative	+ Positive	+ Positive	Higher income supports better environmental action, reduces healthcare cost burden, enhances health outcomes and facilitates investment in renewable energy infrastructure
PA	Population ages 65 and above (% of total population)	– Negative	+ Positive	- Negative or ambiguous ±	- Negative or ambiguous ±	An aging population may reduce environmental focus, increase healthcare costs, and have mixed effects on health outcomes and clean and affordable energy
NRD	Adjusted savings: natural resources depletion (% of GNI)	– Negative	N/A	N/A	- Negative or ambiguous ±	Resource depletion deteriorates environmental sustainability and may either push for renewable alternatives or reflect heavy dependence on non-renewables
HEPC	Current health expenditure per capita (current US$)	N/A	N/A	+ Positive	N/A	Increased health spending is expected to improve health outcomes.
DGGHEPC	Domestic general government health expenditure per capita (current US$)	N/A	N/A	+ Positive	N/A	Higher government health spending should enhance public health outcomes.
DPHEPC	Domestic private health expenditure per capita (current US$)	**N/A**	**N/A**	+ Positive or ambiguous ±	**N/A**	Private health spending may positively or ambiguously affect health, depending on accessibility and equity.

Note: N/A = Not Applicable

The selection was based purely on the availability of the required data. Data were obtained from the UN Sustainable Development Goal Global Database (SDR) and World Bank World Development Indicators (WDI), covering the period from 2005 to 2020. Table 1 presents the key variables and the expected signs across the three estimated models. In Model 1, it is anticipated that renewable energy consumption and GDP per capita will positively influence environmental sustainability (SDG-13), whereas natural resource depletion and an aging population are expected to exert negative effects. In Model 2, environmental sustainability (SDG-13) and renewable energy use are expected to reduce healthcare costs, whereas an aging population may increase costs. For Model 3, both public and private health expenditures, along with GDP per capita, are hypothesized to enhance health outcomes (SDG-3), although private health spending may have an ambiguous effect depending on affordability and access. These expectations are grounded in Energy Transition Theory and the Health Production Model, contextualized within the realities of Sub-Saharan Africa.

3.2. Model specification and estimation strategy

This study introduces three distinct models to examine the interactions among energy transition, environmental sustainability, healthcare costs, and health outcomes in Sub-Saharan Africa (SSA), with a particular emphasis on achieving SDG-3 (Good Health and Well-being), SDG-7 (Affordable and Clean Energy), and SDG-13 (Climate Action). Model 1 investigates the determinants of environmental sustainability (represented by the SDG-13 indicators), focusing on renewable energy consumption, economic performance, demographic structure, and natural resource depletion. This model examines how changes in energy systems and macroeconomic conditions influence the environmental outcomes in SSA. Model 2 reverses causal flow by evaluating the impact of environmental sustainability and energy transition on healthcare costs. Specifically, it investigates whether enhancements in environmental quality and renewable energy consumption help reduce the current health expenditure per capita (HEPC) in the region. Model 3 focuses on the influence of healthcare financing structures on health outcomes. By modelling SDG-3 indicators as the dependent variable, this study explores how domestic government health expenditure, private health expenditure, and total health spending affect the health status of populations across SSA. Model 4 focuses on identifying the factors influencing the achievement of SDG-7 (Affordable and Clean Energy) in sub-Saharan Africa.

It assesses how macroeconomic factors, demographic changes, environmental sustainability, and resource depletion affect access and use of renewable energy. Together, these four models offer a comprehensive multidimensional understanding of the interplay between energy transition, environmental sustainability, healthcare costs, health outcomes, and access to affordable clean energy. By systematically analysing the determinants and interdependencies among SDG-3 (Good Health and Well-Being), SDG-7 (Affordable and Clean Energy), and SDG-13 (Climate Action), this study provides robust policy insights for promoting sustainable development in emerging economies. Given the panel structure of the data (multiple countries observed over time), panel data estimation techniques were employed to address country-specific heterogeneity and improve estimation efficiency. The models are specified as follows:

$$lnSDG13_{it} = a_0 + \alpha_1 \mathrm{lnREC}_{it} + \alpha_2 \mathrm{lnGDPC}_{it} + \alpha_3 \mathrm{lnPA}_{it} + \alpha_4 \mathrm{NRD}_{it} + \varepsilon_{it} \quad (1)$$

$$lnHEPC_{it} = a_0 + \alpha_1 \mathrm{lnREC}_{it} + \alpha_2 \mathrm{lnGDPC}_{it} + \alpha_3 \mathrm{lnPA}_{it} + \alpha_4 \mathrm{NRD}_{it} + \varepsilon_{it} \quad (2)$$

$$lnSDG3_{it} = a_0 + \alpha_1 \mathrm{lnHEPC}_{it} + \alpha_2 \mathrm{lnDGGHEPC}_{it} + \alpha_3 \mathrm{lnDPHEPC}_{it} + \alpha_4 \mathrm{lnGDPC}_{it} + \varepsilon_{it} \quad (3)$$

$$lnSDG7_{it} = a_0 + \alpha_1 \mathrm{lnGDPC}_{it} + \alpha_2 \mathrm{lnPA}_{it} + \alpha_3 \mathrm{lnSDG13}_{it} + \alpha_4 \mathrm{NRD}_{it} + \varepsilon_{it} \quad (4)$$

where *i* and *t*. denote country and year, respectively, α_0 is the constant term, while $\alpha_1 - \alpha_4$ are the estimated coefficients. ε_{it} is the error term, SDG3 is Health outcome indicator (Good Health and Well-Being), SDG7 is Affordable and clean energy indicator, SDG13 is Environmental sustainability indicator, REC is Renewable energy consumption GDPC is GDP per capita, PA is Population Age, is NRD is Natural resources depletion, is HEPC is Health expenditure per capita is DGGHEPC is Domestic general government health expenditure per capita, is DPHEPC is Domestic private health expenditure per capita. To determine the appropriate model between fixed and random effects, the Hausman specification test was conducted. If the Hausman test indicates that the individual effects are correlated with the regressors, the fixed-effects model is preferred. Otherwise, the random-effects model was deemed appropriate.

4. Results and discussion

4.1. Descriptive statistics and correlation analysis

This section presents a comparative analysis of the principal characteristics of each variable across the East, Central, Southern, and West African sub-regions based on the descriptive statistics in Table 2. Health Outcome Indicator (SDG3): East Africa exhibits a mean SDG3 score of 41.42 (SD = 13.45), indicating a moderate level of good health and well-being with notable variation. Central Africa showed a slightly lower mean of 35.02 (SD = 13.91), also with considerable dispersion. Southern Africa had a mean of 36.89 (SD = 10.23), suggesting a similar moderate level, but with relatively less variability. West Africa had a mean of 37.60 (SD = 12.78), indicating a comparable level of health outcomes with moderate variation.

Affordable and Clean Energy Indicator (SDG7): East Africa recorded a mean SDG7 score of 34.31 (SD = 13.82), indicating relatively lower access to affordable and clean energy with significant dispersion. Central Africa showed a slightly higher mean of 37.86 (SD = 19.20) but also with substantial variability. Southern Africa had the highest mean among the four sub-regions at 43.85 (SD = 16.17), suggesting comparatively better access, although still with considerable dispersion. West Africa had the lowest mean of 25.42 (SD = 14.74), indicating the poorest performance in affordable and clean energy access, with notable variation.

Environmental Sustainability Indicator (SDG13): All four sub-regions demonstrated high mean scores for SDG13, indicating strong performance in environmental sustainability. East Africa had a mean of 98.30 (SD = 1.98), Central Africa 94.38 (SD = 6.26), Southern Africa 90.38 (SD = 6.22), and West Africa 98.47 (SD = 0.93). The low standard deviations across all regions suggest a consistently high level of environmental sustainability performance within each subregion. Current Health Expenditure Per Capita (HEPC): There is substantial variation in HEPC across sub-regions. West Africa has the lowest mean HEPC at 53.06 (SD = 32.77). East Africa shows a slightly higher mean of 72.83 (SD = 118.01) with high variability. Central Africa has a mean of 81.49 (SD = 69.38), also with considerable dispersion. Southern Africa exhibits the highest mean HEPC at 344.74 (SD = 162.73), indicating significantly higher health spending per person with substantial variability.

Domestic General Government Health Expenditure Per Capita (DGGHEPC): West Africa has the lowest mean DGGHEPC at 16.06 (SD = 22.04). East Africa shows a slightly higher mean of 25.60 (SD = 54.40) with high variability. Central Africa has a mean of 35.23 (SD = 42.48), also with considerable dispersion. Southern Africa exhibits the highest mean DGGHEPC at 179.36 (SD = 90.03), indicating significantly higher government spending on health per person with substantial variability.

Domestic Private Health Expenditure Per Capita (DPHEPC): West Africa has a mean DPHEPC of 27.55 (SD = 14.96). East Africa shows a higher mean of 33.91 (SD = 66.73) with high variability. Central Africa has a mean of 35.60 (SD = 32.11), also with considerable dispersion. Southern Africa exhibits the highest mean DPHEPC at 123.28 (SD = 83.97), indicating significantly higher private spending on health per person with substantial variability.

Renewable Energy Consumption (% of total final energy consumption) (REC): All four sub-regions show relatively low mean REC values with significant dispersion. Southern Africa has the lowest mean at 36.94 (SD = 20.76), followed by West Africa at 65.64 (SD = 20.70), Central Africa at 73.48 (SD = 19.31), and East Africa with the highest mean at 77.71 (SD = 21.73). This indicates a generally low reliance on renewable energy sources with considerable variation within each region. Natural Resources Depletion (% of GNI) (NRD): The mean NRD values are generally low across the sub-regions. Southern Africa has the lowest mean at 2.59 (SD = 1.47), followed by East Africa at 6.63 (SD = 6.73), West Africa at 6.33 (SD = 5.91), and Central Africa with the highest mean at 15.72 (SD = 13.15). This suggests a relatively limited impact of natural resource depletion on national income, although Central Africa shows a notably higher average and greater variability.

Table 2. Descriptive statistics, source: Authors' computation

Variable	EAST AFRICA		CENTRAL AFRICA		SOUTHERN AFRICA		WEST AFRICA	
	Mean	Min	Mean	Min	Mean	Min	Mean	Min
	(SD)	(Max)	(SD)	(Max)	(SD)	(Max)	(SD)	(Max)
sdg 3	41.41667	19	35.01786	10	36.8875	18	37.58984	17
	(13.44499)	(79)	(13.91479)	(65)	(10.22654)	(55)	(12.77896)	(76)
sdg 7	34.3125	15	37.85714	9	43.85	12	25.42188	2
	(13.81919)	(74)	(19.20626)	(84)	(16.17006)	(70)	(14.74176)	(63)
sdg 13	98.30208	91	94.375	80	90.375	79	98.46875	96
	(1.979581)	(100)	(6.264623)	(100)	(6.220373)	(98)	(0.9325277)	(100)
hepc	72.83717	6.557099	81.48868	8.997461	344.7356	41.15413	53.05992	16.35091
	(118.0084)	(671.8605)	(69.3853)	(283.0319)	(162.7331)	(694.1006)	(32.77415)	(181.442)
dgghepc	25.59571	1.265332	35.23287	0.4613738	179.3639	19.86002	16.05657	1.123269
	(54.39762)	(316.0571)	(42.47726)	(168.6313)	(90.33145)	(360.0105)	(22.04172)	(111.4931)
dphepc	33.91437	2.224864	35.60364	5.415555	123.2754	14.15194	27.54578	5.425179
	(66.72839)	(356.8927)	(32.11348)	(165.0605)	(83.96675)	(284.8347)	(14.99573)	(78.95575)
tge	34010.95	323.94	37688.52	101.55	112280.90	2204.23	31178.63	614.96
	(36233.97)	(150963.1)	(31466.32)	(90124.86)	(210500)	(560857)	(62658.94)	(308179.8)
rec	77.91	8.94	73.48	38.06	36.94	7.72	65.64	20.78
	(21.73378)	(96.01)	(19.31022)	(97.42)	(20.75798)	(72.68)	(20.70314)	(94.42)
nrd	6.628596	0.001942	15.71911	0.0015779	2.592728	0.5665656	6.330882	0.0001475
	(6.728054)	(33.00872)	(13.15389)	(49.15846)	(1.466909)	(7.015718)	(5.912227)	(24.26013)
gdppc	1440.112	263.361	2209.759	338.1657	4136.564	843.5061	1148.832	404.2806
	(2254.367)	(10956.95)	(2063.628)	(7155.366)	(1886.012)	(6485.46)	(754.5159)	(3690.656)
pa	3.242787	1.521082	3.023779	1.996803	3.878086	2.523962	3.153886	2.285074
	(1.851142)	(11.78311)	(0.6382901)	(4.484545)	(0.8435738)	(6.000535)	(0.743103)	(6.21997)

Table 3. Correlation Matrix for Central Africa, source: Authors' computation

	sdg3	**sdg7**	**sdg13**	**hepc**	**dgghepc**	**dphepc**	**tge**	**rec**	**nrd**	**gdppc**	**pa**
sdg3	1.000										
sdg7	0.422	1.000									
sdg13	-0.277	-0.711	1.000								
hepc	0.475	0.806	-0.877	1.000							
dgghepc	0.405	0.751	-0.888	0.951	1.000						
dphepc	0.238	0.807	-0.841	0.886	0.762	1.000					
tge	-0.340	-0.077	0.179	-0.263	-0.241	-0.036	1.000				
rec	-0.623	0.179	0.051	-0.192	-0.160	0.043	0.142	1.000			
nrd	0.026	0.041	-0.530	0.239	0.309	0.267	0.104	-0.060	1.000		
gdppc	0.3639	0.8137	-0.968	0.9372	0.9279	0.8732	-0.2065	-0.0645	0.3724	1.000	
pa	0.7087	0.7143	-0.4988	0.6994	0.5866	0.5915	-0.3653	-0.1543	0.0879	0.617	1.000

Table 4. Correlation Matrix for East Africa, source: Authors' computation

	sdg3	**sdg7**	**sdg13**	**hepc**	**dgghepc**	**dphepc**	**tge**	**rec**	**nrd**	**gdppc**	**pa**
sdg3	1.000										
sdg7	0.607	1.000									
sdg13	-0.693	-0.871	1.000								
hepc	0.764	0.778	-0.908	1.000							
dgghepc	0.745	0.769	-0.903	0.990	1.000						
dphepc	0.770	0.755	-0.885	0.989	0.966	1.000					
tge	-0.227	-0.208	0.196	-0.239	-0.201	-0.250	1.000				
rec	-0.821	-0.828	0.895	-0.892	-0.863	-0.908	0.326	1.000			
nrd	-0.363	-0.487	0.488	-0.349	-0.324	-0.327	0.057	0.481	1.000		
gdppc	0.7948	0.8304	-0.9461	0.9745	0.9628	0.9718	-0.2086	-0.9348	-0.369	1.000	
pa	0.7583	0.7389	-0.8233	0.9087	0.8976	0.9217	-0.2726	-0.9097	-0.373	0.905	1.000

Table 5. Correlation Matrix for Southern Africa, source: Authors' computation

	sdg3	**sdg7**	**sdg13**	**hepc**	**dgghepc**	**dphepc**	**tge**	**rec**	**nrd**	**gdppc**	**pa**
sdg3	1.000										
sdg7	0.466	1.000									
sdg13	-0.735	-0.293	1.000								
hepc	0.795	0.596	-0.825	1.000							
dgghepc	0.900	0.504	-0.834	0.928	1.000						
dphepc	0.650	0.476	-0.813	0.931	0.775	1.000					
tge	0.434	0.431	-0.764	0.590	0.586	0.613	1.000				
rec	-0.659	-0.009	0.914	-0.652	-0.711	-0.672	-0.696	1.000			
nrd	-0.457	-0.273	0.173	-0.368	-0.416	-0.259	0.144	0.050	1.000		
gdppc	0.9133	0.5139	-0.8358	0.8483	0.9143	0.7023	0.528	-0.6692	-0.385	1.000	
pa	0.2293	0.069	-0.476	0.2375	0.2699	0.3502	0.7954	-0.5995	0.3006	0.134	1.000

Table 6. Correlation Matrix for West Africa, source: Authors' computation

	sdg3	**sdg7**	**sdg13**	**hepc**	**dgghepc**	**dphepc**	**tge**	**rec**	**nrd**	**gdppc**	**pa**
sdg3	1.000										
sdg7	0.735	1.000									
sdg13	-0.522	-0.650	1.000								
hepc	0.605	0.668	-0.418	1.000							
dgghepc	0.805	0.705	-0.413	0.851	1.000						
dphepc	0.112	0.423	-0.396	0.730	0.335	1.000					
tge	-0.282	-0.016	-0.235	0.149	-0.075	0.505	1.000				
rec	-0.844	-0.670	0.693	-0.435	-0.642	-0.048	0.232	1.000			
nrd	-0.398	-0.302	0.317	-0.125	-0.270	0.016	-0.124	0.459	1.000		
gdppc	0.5837	0.7373	-0.6637	0.831	0.7833	0.6778	0.4044	-0.5652	-0.327	1.000	
pa	0.6116	0.5007	-0.3353	0.6846	0.8055	0.25	-0.1138	-0.5535	-0.026	0.628	1.000

GDP Per Capita (GDPC): There are significant economic disparities among the sub-regions. West Africa has the lowest mean GDPC at 1148.83 (SD = 754.52). East Africa shows a slightly higher mean of 1440.11 (SD = 2254.36) with high variability. Central Africa has a mean of 2209.76 (SD = 2063.63), also with considerable dispersion. Southern Africa exhibits the highest mean GDPC at 4136.56 (SD = 1886.01), indicating the highest average economic output per person with substantial variability.

Population Age (PA): The mean values for the population age indicator ('pa') are relatively similar across the sub-regions. Central Africa has the lowest mean at 3.02 (SD = 0.64), followed by West Africa at 3.15 (SD = 0.74), East Africa at 3.24 (SD = 1.85), and Southern Africa with the highest mean at 3.88 (SD = 0.84). This suggests some variation in the demographic structures across the regions.

4.2. Cross-sectional dependence, stationarity and cointegration tests

This study examines Environmental Sustainability and Healthcare Costs in Emerging Economies: Implications for SDG-3, SDG-7 and SDG-13 in SSA in SSA 2005 and 2020. Since there can be interdependence among countries, based on geographic closeness or shared socio-economic features, it is pertinent to begin by testing for cross-sectional dependence (CSD), which, if not controlled, can lead to spurious estimates. To determine this, this study implemented the Pesaran (2004, 2007) CD test, which is suitable for both large and small panels. Failure to reject the null hypothesis would indicate that CSD is present. The result of the CSD test score of 12.462, with a probability of 0.0000, indicates the presence of cross-sectional dependence. This study, therefore, employed second-generation unit root tests to ensure strong estimation. The Cross-Sectional Augmented Im, Pesaran, and Shin (CIPS) test and the Cross-Sectionally Augmented Dickey-Fuller (CADF) test are utilized in specific contexts. These tests control for interdependencies across countries through the inclusion of cross-sectional averages, thus producing more reliable stationarity tests in panels with correlated units. The result of the unit root test reported in Table 7 indicates that all the variables are integrated of order zero I(0) and order one I(1) at the 1 and 5% level of significance, respectively.

Table 7. Stationarities of the variables, source: Authors' computation

Variable	CIPS		CADF	
	I(0)	**I(1)**	**I(0)**	**I(1)**
lnHEPC	-2.144	-3.498***	-2.144	-3.498***
lnlnDGGHEPC	-2.678**	-4.016***	-2.678**	-4.016***
lnDPHEPC	-1.993	-3.402***	-1.993	-3.402***
lnTGE	-2.807***	-4.102***	-2.807***	-4.102***
lnREC	-1.960	-3.216***	-1.960	-3.216***
lnNRD	-2.493	-3.486***	-2.493	-3.486***
lnGDPPC	-2.035	-2.835***	-2.035	-2.835***
lnPA	-1.448	-2.422**	-1.448	-2.422**
lnSDG3	-2.80***	-4.157***	-2.80***	-4.157***
lnSDG7	-2.817***	-4.10***	-2.817***	-4.10***
lnSDG13	-1.691	-2.100**	-1.691	-2.100**

Note: ***, ** and * illustrate the 1 %, 5 % and 10 % significance levels, respectively.

The examination of cointegration among the variables underscores the long-term equilibrium relationship suggested by macroeconomic models. To explore potential cross-sectional interdependence, the Pedroni cointegration test was employed. The Pedroni test is designed for heterogeneous panels, allowing for cross-sectional dependence and varying slopes across units. The findings in Table 8 indicate that a cointegrating relationship exists between the dependent variables and the included regressors in the four models. Therefore, the Random Effect (RE) and Fixed Effect (FE) estimation techniques can be engaged to examine the effects of the explanatory variables on the outcome variables (SDG3, HEPC, SDG7, and SDG13).

4.3 Presentation and Discussion of Results

The regression results presented in the earlier table, when analysed in conjunction with the provided variable descriptions, offer nuanced insights into the determinants of the Environmental Sustainability Indicator (lnsdg13) under Model 1 and Health Expenditure Per Capita (lnhepc) under Model 2 across the subregions of Central Africa, East Africa, Southern Africa, and West Africa. A detailed examination of each explanatory variable's impact on these dependent variables across the subregions reveals distinct patterns and policy implications, now with the correct identification of 'lnrec' as the log of Renewable Energy Consumption.

Table 8. Pedroni Panel cointegration test results for Models 1 and 2, source: Authors' computation

Test statistics	MODEL 1: lnSDG 13			
	EAST AFRICA	CENTRAL AFRICA	SOUTHERN AFRICA	WEST AFRICA
	1	2	3	4
Pedroni Cointegration Test				
Modified Phillips–Perron t	4.4032***	2.2784***	1.221	4.5789***
Phillips–Perron t	-0.7221	-2.3286***	-2.9602***	-4.792***
Augmented Dickey–Fuller t	-0.0405	-2.8307***	-3.1921***	-1.8822**
Test statistics	MODEL 2: lnHEPC			
	EAST AFRICA	CENTRAL AFRICA	SOUTHERN AFRICA	WEST AFRICA
	1	2	3	4
Pedroni Cointegration Test				
Modified Phillips–Perron t	2.3483***	1.7058**	2.8238***	4.0548***
Phillips–Perron t	-7.0788***	-6.5321***	1.1605	-1.5721**
Augmented Dickey–Fuller t	-6.4427***	-3.6668***	0.2782	-2.6816***

Note: ***, **, and * illustrate the 1 %, 5 %, and 10 % significance levels, respectively.

Table 9. Pedroni Panel cointegration test results for Models 3 and 4, source: Authors' computation

Test statistics	MODEL 3: lnSDG 3			
	EAST AFRICA	CENTRAL AFRICA	SOUTHERN AFRICA	WEST AFRICA
	1	2	3	4
Pedroni Cointegration Test				
Modified Phillips–Perron t	2.7522***	2.6724***	1.9956**	3.685***
Phillips–Perron t	-2.325***	-0.1286	-1.2375	-1.7041**
Augmented Dickey–Fuller t	-2.1884***	0.1316	-0.8113	-1.9254**
Test statistics	MODEL 4: lnSDG 7			
	EAST AFRICA	CENTRAL AFRICA	SOUTHERN AFRICA	WEST AFRICA
	1	2	3	4
Pedroni Cointegration Test				
Modified Phillips–Perron t	2.7413***	1.9081**	1.9933**	2.8993***
Phillips–Perron t	-3.2938***	-5.1942***	-0.173	-3.6571***
Augmented Dickey–Fuller t	-2.912***	-5.2917***	-0.0078	-3.7516***

Note: ***, **, and * illustrate the 1 %, 5 %, and 10 % significance levels, respectively.

*4.3.1. **Model 1:** SDG13 – Determinants of environmental sustainability*

From the result of Model 1 reported in Table 10, the influence of the log of renewable energy consumption (lnrec) varies across the subregions. In Central Africa, a positive and statistically significant coefficient of 0.049 ($p<0.01$) suggests that higher renewable energy consumption is associated with improved environmental sustainability. A similar, albeit smaller, positive and significant effect is observed in East Africa (0.016, $p<0.01$). These findings strongly imply that increasing the adoption of renewable energy sources in these regions can contribute to a more environmentally sustainable trajectory. However, Southern Africa exhibits a negative and significant coefficient of -0.018 ($p<0.05$), indicating a counterintuitive relationship where higher renewable energy consumption is associated with decreased environmental sustainability. This unexpected result warrants further investigation into the specific types of renewable energy adopted and potential indirect effects or data anomalies. West Africa shows a weak positive and significant coefficient of 0.008 ($p<0.01$), suggesting a modest positive link between renewable energy consumption and environmental sustainability. The policy implication is clear: promoting renewable energy consumption in Central and East Africa appears to be a viable strategy for enhancing environmental sustainability. Southern Africa needs to carefully examine its renewable energy sector to understand why it is negatively associated with environmental sustainability, while West Africa should aim to strengthen the positive link.

The log of GDP per capita (lngdppc) in consistently demonstrates a negative and statistically significant association with environmental sustainability across all subregions: Central Africa (-0.029, $p<0.01$), East Africa (-0.010, $p<0.01$), Southern Africa (-0.082, $p<0.01$), and West Africa (-0.008, $p<0.01$). This robust finding suggests that higher levels of economic development, as measured by GDP per capita, are correlated with lower environmental sustainability. This aligns with the concept of an environmental Kuznets curve, where environmental degradation initially worsens with economic growth before potentially improving at higher income levels; these results indicate a negative relationship within the observed income ranges in these subregions. The policy implication is the urgent need for policies that decouple economic growth from environmental degradation, such as investing in green technologies, enforcing stricter environmental regulations, and promoting sustainable consumption and production patterns.

The impact of the log of Population Age (lnpa) on environmental sustainability in Model 1 is regionally diverse. Central Africa (-0.076, $p<0.01$) and West Africa (-0.011, $p<0.05$) show a negative and significant relationship, suggesting that a larger elderly population is associated with lower environmental sustainability in these regions. This could be related to different consumption patterns or a lower adoption rate of environmentally friendly practices among older demographics in these areas. Conversely, Southern Africa exhibits a positive and significant coefficient (0.078, $p<0.01$), implying that a larger elderly population may contribute to greater environmental sustainability, perhaps through more environmentally conscious behaviours or a greater emphasis on conservation. East Africa shows an insignificant coefficient (-0.002). Policy responses should consider these demographic nuances, potentially involving targeted environmental awareness campaigns aimed at different age groups within each subregion.

The log of Natural Resources Depletion (lnrd) in exhibited statistically insignificant coefficients in all of the subregions (Central Africa: -0.001, East Africa: 0.000, Southern Africa: 0.004, West Africa: 0.000). This suggests that, based on this model, there is no direct statistically significant linear relationship between natural resources depletion and environmental sustainability at the subregional level. However, the indirect effects of resource depletion on economic activities that impact the environment cannot be discounted.

4.3.1.1. Regional and Temporal Dynamics of Environmental Sustainability Drivers: A Pre- and During-COVID Analysis

The log of renewable energy consumption (lnrec) presents a markedly different narrative before and during the pandemic. Pre-COVID, renewable energy adoption strongly promoted environmental sustainability in Central Africa (0.042 $p < 0.01$), East Africa (0.022 $p < 0.01$) and, to a lesser extent, West Africa (0.009 $p < 0.01$), whereas Southern Africa showed no discernible link (–0.020, not significant). These results demonstrate the important function of clean-energy expansion in driving climate-action progress across much of the continent. During COVID, however, lnrec lost statistical significance everywhere (Central Africa –0.019, East Africa – 0.022, Southern Africa – 0.275, West Africa – 0.035; all ns), suggesting that pandemic-induced economic disruptions, shifting energy use patterns, or data collection challenges obscured the earlier benefits. Policymakers therefore need to restore momentum behind renewable-energy investments, especially where previous gains have stalled, and to investigate why Southern Africa's coefficient, while positive, remains imprecisely estimated.

The log of GDP per capita (lngdppc) consistently revealed a growth–environment trade-off prior to COVID-19: Central Africa (–0.025 $p < 0.01$), East Africa (–0.009 $p < 0.01$), Southern Africa (–0.092 $p < 0.05$) and West Africa (–0.008 $p < 0.01$). These values indicate that rising incomes were generally realised through emission-intensive pathways, echoing the downward segment of the environmental Kuznets hypothesis within the observed income range. During the pandemic this relationship weakened or vanished in most regions (Central Africa –0.115 ns; Southern Africa 0.131 ns; West Africa –0.011 ns) but remained significantly negative in East Africa (–0.092 $p < 0.05$). Temporary lockdown-related slowdowns may explain the broader attenuation, yet East Africa's persistent signals deeper structural dependence on carbon-intensive growth. Decoupling policies, green industrialisation, tighter environmental standards and incentives for low-carbon technologies are therefore urgent, with region-specific tailoring for East Africa.

Population age (lnpa) exhibits clear regional nuance. Before COVID-19, a larger elderly cohort correlated with lower environmental sustainability in Central Africa (–0.084 $p < 0.01$) and West Africa (–0.013 $p < 0.01$), but with higher sustainability in Southern Africa (0.076 $p < 0.01$); East Africa showed no relationship (–0.004 ns). The differences may reflect consumption patterns, environmental awareness, or generational policy priorities. During COVID-19, coefficients flipped sign or lost significance in every sub-region (Central Africa 0.360 ns; East Africa 0.050 ns; Southern Africa 0.071 ns; West Africa 0.129 ns). The pandemic appears to have disrupted demographic–

environment linkages, perhaps because immediate health and economic concerns overshadowed age-related behavioural effects. Targeted awareness campaigns, adjusted for each region's demographic profile, remain advisable once stability returns.

Table 10. Estimated results from Model 1: SDG 13 with COVID-19 Dynamics, source: Authors' estimation

	CENTRAL AFRICA			EAST AFRICA			SOUTHERN AFRICA			WEST AFRICA		
	AGGRE-GATE	PRE-COVID	DURING-COVID	AGGRE-GATE	PRE-COVID	DURING-COVID	AGGRE-GATE	PRE-COVID	DURING-COVID	AGGRE-GATE	PRE-COVID	DURING-COVID
lnrec	0.049***	0.042***	-0.019	0.016***	0.022***	0.022	-0.018	-0.02	0.275	0.008***	0.009***	-0.035
	(0.014)	(0.013)	(0.056)	(0.004)	(0.004)	(0.044)	(0.024)	(0.027)	(0.253)	(0.003)	(0.003)	(0.025)
	[3.44]	[3.31]	[-0.35]	[4.23]	[5.15]	[0.49]	[-0.77]	[-0.74]	[1.08]	[2.91]	[3.13]	[-1.41]
lngdppc	-0.029***	-0.025***	-0.115	-0.010***	-0.009***	-0.092**	-0.082***	-0.072**	0.131	-0.008***	-0.008***	-0.011
	(0.009)	(0.009)	(0.064)	(0.002)	(0.002)	(0.034)	(0.030)	(0.034)	(0.306)	(0.002)	(0.002)	(0.014)
	[-3.21]	[-2.78]	[-1.78]	[-5.62]	[-4.63]	[-2.71]	[-2.75]	[-2.14]	[0.43]	[-3.86]	[-3.26]	[-0.83]
lnpa	-0.076***	-0.084***	0.36	-0.002	-0.004	0.05	0.078***	0.076***	0.071	-0.011**	-0.013**	0.129
	-0.023	(0.023)	(0.337)	-0.003	(0.003)	(0.117)	-0.019	(0.025)	(0.668)	-0.005	(0.005)	(0.086)
	[-3.27]	[-3.69]	[1.07]	[-0.79]	[-1.3]	[0.43]	[4.08]	[3.07]	[0.11]	[-2.35]	[-2.54]	[1.51]
lnnrd	-0.001	-0.0005	-0.006	0.0002	0.001*	-0.006	0.004	0.005	0.073	-0.0003	0	-0.006**
	(0.002)	(0.002)	(0.007)	(0.00046)	0.000	(0.003)	(0.003)	(0.004)	(0.074)	0.0002	0.000	(0.003)
	[-0.63]	[-0.28]	[-0.93]	[0.37]	[1.98]	[-1.72]	[1.19]	[1.4]	[0.98]	[-1.44]	[-1.26]	[-2.24]
cons	4.6343***	4.638***	5.088***	4.592***	4.559***	5.407***	5.123	5.054***	2.372	4.623	4.520***	4.668***
	(0.117)	(0.11)	(0.79)	0.025	(0.03)	(0.37)	(0.292)	(0.33)	(4.05)	(0.023)	(0.03)	(0.19)
	[39.51]	[43.27]	[6.480]	[181.57]	[159.4]	[13.64]	[17.54]	[15.2]	[0.59]	[197.34]	[180.73]	[24.25]
Obs.	112	98	14	192	168	24	80	70	10	256	224	32
R^2	0.328	0.294	0.826	0.417	0.494	0.751	0.203	0.151	0.864	0.185	0.176	0.443
Adj. R^2	0.261	0.213	0.248	0.368	0.444	0.285	0.114	0.039	-0.226	0.119	0.099	-0.439

***, **, * denotes significance levels at 1%, 5%, and 10% respectively. The dependent variables is Sustainable Development Goal 13 (lnSDG13). The standard errors are in parentheses, while the t-statistics are in braces.

4.3.1.2. Synthesis and policy insight

Before the pandemic, renewable-energy expansion emerged as the clearest lever for advancing SDG 13 in most African sub-regions, whereas economic growth was predominantly carbon-intensive. COVID-19 weakened many of these relationships, hinting at both reprieves (reduced growth-related emissions) and emerging threats (resource pressures in West Africa). A recovery strategy that reinvigorates clean-energy deployment, embeds environmental conditions in stimulus spending, and tailors' interventions to each region's demographic and resource context will be essential for realigning growth trajectories with climate-action goals and accelerating the continent's march towards SDG 13.

4.3.2. ***Model 2:*** *HEPC – impact of environmental sustainability and energy transition on healthcare costs*

Before COVID-19, natural-resource depletion (lnnrd) didn't have much impact: the numbers were not significant in Central Africa (–0.0005), Southern Africa (0.005), and West Africa (0.000), while East Africa showed a small positive link (0.001 $p < 0.10$), which might be due to new restoration efforts or errors in measurement. During the pandemic, resource pressure became materially harmful only in West Africa (–0.006 $p < 0.05$), with all other regions being insignificant (Central Africa –0.006; East Africa –0.003; Southern Africa 0.073). This shift signals that COVID-19 may have intensified extractive stresses or revealed latent vulnerabilities in West Africa. Improving how natural resources are managed and increasing environmental protections are very important in West Africa, while the unusual findings in East Africa need a deeper look at the data and specific policies for that area.

4.3.1.2. Synthesis and policy insight

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In this model, we reversed the causal flow to model 1 by evaluating the impact of environmental sustainability and energy transition on healthcare costs (lnhepc). The result as presented in Table 11 columns show that the log of Renewable Energy Consumption (lnrec) demonstrates a strong negative and statistically significant relationship across all subregions: Central Africa (-0.963, $p<0.01$), East Africa (-0.618, $p<0.01$), Southern Africa (-0.771, $p<0.01$), and West Africa (-0.771, $p<0.01$). This intriguing finding suggests that higher renewable energy consumption is associated with lower health expenditure per capita. This could indicate that investments in renewable energy may lead to a healthier environment, reducing the burden of pollution-related diseases and lowering health expenditure. Alternatively, it might reflect a trade-off in resource allocation, where greater investment in the renewable energy sector could, in the short term, divert resources from health spending. Further research is needed to disentangle these potential mechanisms. The policy implication is to investigate the pathways through which renewable energy consumption affects health expenditure to optimize resource allocation and maximize both environmental and health benefits.

The log of GDP per capita (lngdppc) in Model 2 shows a positive and statistically significant relationship with health expenditure per capita across all subregions: Central Africa (0.705, $p<0.05$), East Africa (1.129, $p<0.01$), Southern Africa (1.326, $p<0.01$), and West Africa (1.326, $p<0.01$). This indicates that higher levels of economic development are associated with greater health expenditure per capita, likely reflecting increased affordability and investment in healthcare services as economies grow. Therefore, subregional governments need to foster economic growth as a means to enhance the financial capacity for health spending, thereby potentially improving healthcare access and quality.

The log of Population Age (lnpa) in Model 2 presents a mixed impact on health expenditure per capita. Central Africa (0.929, $p<0.1$) and East Africa (0.250, $p<0.1$) exhibit positive and significant coefficients, suggesting that a larger elderly population is associated with higher health expenditure, likely due to increased healthcare needs associated with aging. In contrast, Southern Africa (-0.968, $p<0.01$) and West Africa (-0.968, $p<0.01$) show negative and significant coefficients, indicating that a larger elderly population is associated with lower health expenditure per capita. This unexpected finding might reflect differences in healthcare systems, social support structures, or the prioritization of healthcare spending for the elderly in these subregions. Policy responses should be tailored to these regional variations to ensure equitable and adequate healthcare provision for aging populations.

Finally, the log of Natural Resources Depletion (lnrd) in reveals divergent effects on health expenditure per capita across the subregions. Central Africa shows a positive and significant coefficient (0.086, $p<0.1$), suggesting that higher natural resource depletion is associated with increased health expenditure. This could be due to health problems from environmental degradation associated with resource extraction. East Africa has a positive but statistically insignificant coefficient (0.02). Conversely, Southern Africa (-0.033, $p<0.05$) and West Africa (-0.033, $p<0.05$) exhibit negative and significant coefficients, indicating that higher natural resource depletion is associated with lower health expenditure. This counterintuitive result warrants further investigation into the specific dynamics of resource depletion and health spending in these regions. Policy considerations should include mitigating the negative health consequences of resource depletion and ensuring that resource revenues, where applicable, are channelled towards health sector investments.

Table 11. Estimated results from Model 2: HEPC with COVID-19 dynamics, source: Authors' estimation

	CENTRAL AFRICA			EAST AFRICA			SOUTHERN AFRICA			WEST AFRICA		
	AGGRE-GATE	PRE-COVID	DUR-ING-COVID	AGGRE-GATE	PRE-COVID	DUR-ING-COVID	AGGRE-GATE	PRE-COVID	DUR-ING-COVID	AGGRE-GATE	PRE-COVID	DUR-ING-COVID
lnsdg13	-3.734	-7.339**	13.263	-10.495***	-12.097***	-0.939	0.944	-0.068	0.729	-6.538	-8.311*	-2.207
	(2.639)	(2.919)	(21.990)	(3.705)	(4.278)	(7.308)	(1.455)	(1.599)	(.)	(3.988)	(4.302)	(13.086)
	[-1.41]	[-2.51]	[0.6]	[-2.83]	[-2.83]	[-0.13]	[0.65]	[-0.04]		[-1.64]	[-1.93]	[-0.17]
lnrec	-0.779*	-0.728*	-2.593	-0.450**	-0.488**	-1.297	-0.754**	-0.710**	-1.606	0.425**	0.501***	-0.854
	(0.401)	(0.367)	(2.161)	(0.195)	(0.242)	(0.928)	(0.293)	(0.341)	(.)	(0.170)	(0.185)	(1.209)
	[-1.94]	[-1.98]	[-1.2]	[-2.31]	[-2.02]	[-1.4]	[-2.57]	[-2.08]		[2.5]	[2.71]	[-0.71]
lng-dppc	0.595**	0.625**	0.086	1.021***	1.099***	0.611	1.403***	1.500***	-1.339	1.721***	1.850***	-0.236
	(0.256)	(0.253)	(3.517)	(0.098)	(0.110)	(0.969)	(0.383)	(0.436)	(.)	(0.137)	(0.150)	(0.629)
	[2.33]	[2.47]	[0.02]	[10.43]	[10.03]	[0.63]	[3.67]	[3.44]		[12.53]	[12.32]	[-0.37]
lnpa	0.645	0.074	5.603	0.226	0.057	0.436	-1.043***	-1.071***	-7.384	0.688**	0.760**	2.384
	-0.648	(0.669)	(15.086)	-0.149	(0.182)	(2.441)	-0.262	(0.332)	(.)	-0.297	(0.325)	(4.244)
	[1]	[0.11]	[0.37]	[1.52]	[0.31]	[0.18]	[-3.99]	[-3.23]		[2.31]	[2.34]	[0.56]
lnnrd	0.082*	0.068	0.084	0.021	0.03	-0.1	-0.037	-0.024	-0.493	0.009	0.014	-0.122
	(0.047)	(0.044)	(0.289)	(0.023)	(0.025)	(0.078)	(0.043)	(0.049)	(.)	(0.012)	(0.013)	(0.137)
	[1.74]	[1.54]	[0.29]	[0.95]	[1.18]	[-1.29]	[-0.86]	[-0.48]		[0.78]	[1.13]	[-0.89]
_cons	19.1549	35.723**	-51.997	46.685***	53.851***	8.97	-6.037	-2.403	29.715	18.511	26.331	16.636
	(12.618)	(13.851)	(115.815)	(17.056)	(19.563)	(37.871)	(8.269)	(9.087)	(.)	(18.511)	(19.939)	(61.709)
	[1.52]	[2.58]	[-0.45]	[2.74]	[2.75]	[0.24]	[-0.73]	[-0.26]		[1.05]	[1.32]	[0.27]
Obs.	112	98	14	192	168	24	80	70	10	80	224	32
R^2	0.265	0.33	0.619	0.657	0.669	0.581	0.496	0.503	1	0.562	0.494	0.134
Adj. R^2	0.184	0.245	-1.476	0.625	0.634	-0.378	0.431	0.429	.	0.431	0.444	-1.441

***, **, * denotes significance levels at 1%, 5%, and 10% respectively. The dependent variables is health expenditure per capita (lnHEPC). The standard errors are in parentheses, while the t-statistics are in braces.

4.3.2.1. Disruptions and continuities in health spending: evidence from African Sub-Regions before and during the COVID-19 pandemic

The log of environmental sustainability (lnsdg13) reveals a consistent inverse relationship with health expenditure across most African sub-regions prior to the pandemic. In Central Africa (–7.339, $p < 0.05$), East Africa (–12.097, $p < 0.01$), and West Africa (–8.311, $p < 0.10$), improvements in environmental sustainability were associated with lower per capita health expenditure, suggesting that healthier environmental conditions may reduce disease burdens and consequently healthcare costs. Southern Africa (–0.068, ns) showed no statistically significant relationship. These findings reinforce the health co-benefits of climate action, in line with SDG 13's broader public health dividends. However, during the pandemic, the strength and direction of these relationships changed. In Central Africa, the coefficient became positive but remained statistically insignificant at 13.263 (ns), while East Africa recorded a coefficient of –0.939 (ns), Southern Africa had 0.729 (ns), and West Africa showed –2.207 (ns), all indicating statistically insignificant effects. This shift likely reflects the overriding pressure of emergency pandemic spending, which obscured the longer-term savings typically linked to environmental improvements.

The log of renewable energy consumption (lnrec) showed a strong negative link to health spending before COVID-19 in Central Africa (–0.728, $p < 0.10$), East Africa (–0.488, $p < 0.05$), and Southern Africa (–0.710, $p < 0.05$), suggesting that using cleaner energy might lower healthcare costs by reducing diseases caused by pollution. In West Africa, however, there was an unexpected positive relationship (0.501, $p < 0.05$), which might be due to the costs of switching to renewable energy, spending on infrastructure, or changes in industries that indirectly affect health. During the pandemic, lnrec was no longer significant in all regions (Central Africa –2.593, East Africa –1.297, Southern Africa –1.606, West Africa –0.854; all not significant), suggesting that the health benefits of using renewable energy were likely overshadowed by the urgent healthcare needs caused by COVID-19.

The log of GDP per capita (lngdppc) followed expectations prior to the pandemic, demonstrating a robust and positive relationship with health expenditure across all sub-regions. Central Africa (0.625, $p < 0.05$), East Africa (1.099, $p < 0.01$), Southern Africa (1.500, $p < 0.01$), and West Africa (1.850, $p < 0.01$) all demonstrated that higher income levels were associated with greater per capita health spending. This conclusion reflects the typical wealth–health expenditure linkage observed globally. During COVID-19, however, this association weakened and turned insignificant across the board (Central Africa: 0.086, East Africa: 0.611, Southern Africa: 1.339, West Africa:0.236; all ns). In Southern and West Africa, the sign of the coefficients even reversed. These results suggest that pandemic-induced fiscal reallocations, economic slowdowns, and prioritising emergency responses disrupted the conventional relationship between income and health system funding.

Population age (lnpa) displayed notable regional variation. Before COVID-19, a higher average population age was significantly associated with lower health expenditure in Southern Africa (–1.071, $p < 0.01$), a surprising result that may reflect limited access to healthcare among older populations or structural underinvestment in elderly care. West Africa, by contrast, showed a positive and significant relationship (0.760, $p < 0.05$), more consistent with established expectations that ageing populations drive up healthcare costs. Central Africa (0.074, ns) and East Africa (0.057, ns) showed no significant effects. During the pandemic, coefficients for lnpa shifted or became statistically insignificant across all regions (Central Africa 5.603, East Africa 0.436, Southern Africa –7.384, West Africa 2.384; all ns), highlighting the uniformity of COVID-19's impact across age groups and its capacity to decouple demographic trends from health expenditure dynamics.

Natural resource depletion (LNNRD) did not exhibit a statistically significant relationship with health expenditure in any subregion before the pandemic. Coefficients remained insignificant in Central Africa (0.068), East Africa (0.030), Southern Africa (–0.024), and West Africa (0.014), suggesting that resource depletion did not exert a direct impact on healthcare costs in this model. During COVID-19, the insignificance persisted across all regions – Central Africa (0.084), East Africa (–0.–100), Southern Africa (–0.493), and West Africa (–0.122), further confirming that health expenditure during the pandemic was driven by broader systemic shocks rather than by environmental resource pressures.

4.3.2.2. Synthesis and policy insight

Prior to the pandemic, environmental sustainability and renewable energy consumption were strongly associated with lower health expenditures in several sub-regions, confirming that climate action and clean energy adoption yield tangible public health and economic benefits. However, the onset of COVID-19 disrupted these relationships, with most variables losing statistical significance and several coefficients reversing direction. This pattern underscores how crisis-driven health financing can overshadow longer-term systemic drivers, such as environmental quality, energy infrastructure, and demographic transitions. The attenuation of GDP's positive impact on health expenditure during the pandemic suggests fiscal stress and shifting public priorities, while the disappearance of age-related effects highlights the pandemic's cross-cutting health burden. Moving forward, policy strategies should aim to re-anchor health systems on resilient foundations by integrating environmental sustainability into public health planning. This is especially vital in regions where pre-COVID linkages were strongest. After the pandemic, we have a chance to adjust health spending to match climate goals, supporting both SDG3 and SDG13 together through eco-friendly health funding, access to clean energy, and specific policies for different population groups.

*4.3.3. **Model 3:** SDG3 – the influence of healthcare financing structures on good health and well-being*

The regression results presented in Table 12, examine the determinants of the Health Outcome Indicator (lnsdg3) across four subregions of Africa: Central Africa, East Africa, Southern Africa, and West Africa. The analysis focuses on the influence of the log of GDP per capita (lngdppc), the log of Health Expenditure Per Capita (lnhepc), the log of Domestic General Government Health Expenditure Per Capita (lndgghepc), and the log of Domestic Private Health Expenditure Per Capita (lndphepc) on health outcomes within each subregion.

The log of GDP per capita (lngdppc), demonstrated a consistent positive and statistically significant relationship with the Health Outcome Indicator (lnsdg3) across all subregions. Central Africa exhibits a significant positive coefficient of 0.267 ($p<0.05$), East Africa shows a stronger positive and highly significant coefficient of 0.871 ($p<0.001$), while Southern Africa (0.962, $p<0.001$) and West Africa (0.945, $p<0.001$) display even larger and highly significant positive coefficients. These findings robustly indicate that higher levels of economic development, as proxied by GDP per capita, are strongly associated with better health outcomes across the continent. The policy implication is clear: fostering economic growth is a crucial pathway to improving the overall health and well-being of populations in these African subregions.

The impact of the log of Health Expenditure Per Capita (lnhepc) on the Health Outcome Indicator (lnsdg3) presents a more nuanced picture. Central Africa shows a positive but statistically insignificant coefficient (0.149). East Africa also exhibits a positive and insignificant coefficient (0.028). However, Southern Africa (-0.253, $p<0.1$) and West Africa (-0.117, $p<0.1$) both display negative and statistically significant coefficients. This suggests that while higher overall health expenditure per capita does not significantly correlate with improved health outcomes in Central and East Africa, it is associated with worse health outcomes in Southern and West Africa. This counterintuitive finding may point towards inefficiencies in health spending, misallocation of resources, or other underlying factors that diminish the effectiveness of health expenditure in these latter two subregions. The policy implication is a critical need to examine the efficiency and allocation of health spending in Southern and West Africa to ensure that increased expenditure translates into tangible improvements in health outcomes.

Examining the log of Domestic General Government Health Expenditure Per Capita (lndgghepc), a positive and statistically significant relationship with the Health Outcome Indicator (lnsdg3) is observed in East Africa (0.100, $p<0.01$) and Southern Africa (0.327, $p<0.001$). This indicates that increased government investment in health services is associated with better health outcomes in these subregions. Central Africa and West Africa, however, show a positive but statistically insignificant coefficient (0.024 and 0.116). The policy implication underscores the importance of strong public sector involvement in healthcare financing and provision, particularly in East and Southern Africa, to drive improvements in population health. Governments in these regions should prioritize and efficiently allocate public funds to the health sector.

Finally, the log of Domestic Private Health Expenditure Per Capita (lndphepc) reveals a negative and statistically significant relationship with the Health Outcome Indicator (lnsdg3) in West Africa (-0.152, $p<0.001$). This indicates that a higher private health expenditure per capita is associated with better health outcomes. The policy implication is that governments in West Africa should encourage increased private sector investment in healthcare by creating enabling environments, such as tax incentives, regulatory support, and public-private partnerships, as higher private health expenditure per capita is linked to improved health outcomes. East Africa (-0.150, $p<0.001$). Central Africa (-0.034) and Southern Africa (-0.063) both exhibit negative but statistically insignificant coefficients. The significant negative association in East Africa suggests that higher private health expenditure per capita is associated with worse health outcomes. This could potentially reflect issues related to inequitable access, where private healthcare may not effectively serve the broader population, or it might indicate higher out-of-pocket expenses leading to delayed or forgone care for some segments of the population. The policy implication for East Africa is to carefully examine the role and impact of private health expenditure on overall health outcomes, potentially focusing on regulations and policies that ensure equitable access and quality of care across both public and private sectors.

4.3.3.1. Regional and temporal dynamics of health determinants: a pre- and during-COVID analysis of SDG 3 in SSA

The log of health expenditure per capita (lnhepc) was positively associated with excellent health and well-being in Central Africa (0.214, $p < 0.05$) and East Africa (0.148, $p < 0.10$) before the pandemic, suggesting that increased health investment contributed meaningfully to SDG 3 achievement in these regions. In Southern Africa (–0.191) and West Africa (–0.087), however, the coefficients were negative and statistically insignificant, indicating that higher spending did not necessarily translate to better outcomes—possibly due to inefficiencies in spending or systemic healthcare challenges. During the COVID-19 period, all regions recorded statistically insignificant effects: Central Africa (–0.071), East Africa (–0.055), Southern Africa (–0.863), and West Africa (0.136). The disappearance of statistical significance during the pandemic suggests that emergency health spending may have been narrowly targeted toward crisis responses, with limited immediate impact on broader population health indicators captured under SDG 3.

Table 12. Estimated Results from Model 3: SDG 3 with COVID-19 Dynamics, source: Authors' estimation

	CENTRAL AFRICA			EAST AFRICA			SOUTHERN AFRICA			WEST AFRICA		
	AGGRE-GATE	PRE-COVID	DURING-COVID	AGGRE-GATE	PRE-COVID	DURING-COVID	AGGRE-GATE	PRE-COVID	DURING-COVID	AGGRE-GATE	PRE-COVID	DURING-COVID
lnhepc	0.149	0.214**	-0.071	0.028	0.148*	-0.055	-0.253*	-0.191	-0.863	-0.117**	-0.087	0.136
	(0.095)	-0.09	-0.093	(0.078)	-0.078	-0.145	(0.142)	-0.134	-0.69	(0.142)	-0.057	-0.129
	[1.56]	[2.38]	[-0.77]	[0.36]	[1.91]	[-0.38]	[-1.78]	[-1.42]	[-1.25]	[-2.05]	[-1.52]	[1.05]
lndgghepc	0.024	-0.006	0.05	0.100***	0.046	0.04	0.327***	0.186*	1.155	0.023	0.001	-0.073
	(0.038)	-0.036	-0.037	(0.035)	-0.034	-0.066	(0.116)	-0.107	-0.645	(0.116)	-0.022	-0.055
	[0.64]	[-0.17]	[1.35]	[2.83]	[1.34]	[0.62]	[2.82]	[1.74]	[1.79]	[1.05]	[0.02]	[-1.33]
lndphepc	-0.034	-0.054	0.01	-0.150***	-0.169***	-0.058	-0.063	0.042	-0.037	0.152***	0.151***	-0.044
	(0.076)	-0.073	-0.086	(0.044)	-0.044	-0.092	(0.072)	-0.063	-0.576	(0.072)	-0.047	-0.166
	[-0.45]	[-0.73]	[0.12]	[-3.41]	[-3.87]	[-0.63]	[-0.88]	[0.67]	[-0.06]	[3.24]	[3.23]	[-0.27]
lngdppc	0.267**	0.399***	0.01	0.871***	0.851***	0.212	0.962***	1.083***	0.106	0.945***	0.900***	-0.025
	-0.112	-0.118	-0.146	-0.085	-0.088	-0.167	-0.16	-0.138	[0.11]	-0.16	-0.085	-0.169
	[2.39]	[3.38]	[0.07]	[10.22]	[9.7]	[1.26]	[6.03]	[7.87]	[0.34]	[11.55]	[10.59]	[-0.15]
_cons	0.948	-0.145	3.620**	-2.152	-2.301***	2.687**	-4.202	-5.335***	2.058	-3.0003***	-2.765***	3.736***
	(0.807)	-0.833	-1.085	(0.467)	-0.477	-1.014	(1.200)	-1.024	-5.978	(0.489)	-0.509	-1.126
	[1.18]	[-0.17]	[3.34]	[-4.61]	[-4.82]	[2.65]	[-3.5]	[-5.21]	[0.34]	[-6.13]	[-5.43]	[3.32]
Obs.	112	98	14	192	168	24	80	70	10	80	224	32
R^2	0.244	0.345	0.382	0.654	0.681	0.214	0.544	0.646	0.828	0.544	0.562	0.132
Adj. R^2	0.169	0.27	-1.679	0.624	0.649	-1.259	0.492	0.6	-0.551	0.492	0.521	-1.243

***, **, * denotes significance levels at 1%, 5%, and 10% respectively. The dependent variables here IS the sustainable development goals measured as lnSDG3. The standard errors are in parentheses, while the t-statistics are in braces.

The log of domestic general government health expenditure per capita (lndgghepc) showed a positive and statistically significant effect in Southern Africa (0.186, $p < 0.10$) before COVID-19, indicating that public health spending contributed to improvements in population health in that sub-region. In contrast, the relationship was statistically insignificant in Central Africa (–0.006), East Africa (0.046), and West Africa (0.001), pointing to a limited or delayed impact of government expenditure in these areas. During the pandemic, government health spending remained statistically insignificant across all regions: Central Africa (0.050), East Africa (0.040), Southern Africa (1.155), and West Africa (–0.073). Interestingly, even though Southern Africa's coefficient increased substantially in magnitude, it still wasn't statistically significant, probably showing that while government spending went up during the pandemic, it didn't lead to better health results that could be measured by SDG 3 indicators.

The log of domestic private health expenditure per capita (lndphepc) produced sharply contrasting results across sub-regions before the pandemic. In East Africa, a strong and negative association (–0.169, $p < 0.01$) suggests that higher private spending may have reflected distress financing or inequitable access, contributing to poorer health outcomes. West Africa, by contrast, displayed a positive and significant relationship (0.151, $p < 0.01$), indicating that private health expenditure supported better health results in that region, possibly through effective service provision or complementary healthcare systems. Central Africa (–0.054) and Southern Africa (0.042) exhibited statistically insignificant effects. During the pandemic, all regions recorded statistically insignificant coefficients: Central Africa (0.010), East Africa (–0.058), Southern Africa (–0.037), and West Africa (–0.044). These shifts highlight a potential collapse in private-sector health system functionality during COVID-19 or a redirection of demand toward public health infrastructure, with private expenditures failing to produce measurable improvements in population well-being.

The log of GDP per capita (lngdppc) showed a robust and statistically significant positive relationship with SDG 3 across all sub-regions prior to the pandemic. Central Africa (0.399, $p < 0.01$), East Africa (0.851, $p < 0.01$), Southern Africa (1.083, $p < 0.01$), and West Africa (0.900, $p < 0.01$) all demonstrated that higher economic prosperity translated into better health outcomes, reflecting improved infrastructure, living conditions, and access to health services. However, during COVID-19, this consistent pattern deteriorated, with all regions recording statistically insignificant coefficients: Central Africa (0.010), East Africa (0.212), Southern Africa (0.106), and West Africa (–0.025). The disruption of this relationship indicates that the health crisis affected the link between the economy and health development, possibly due to changes in government spending, a shrinking economy, or the high pressure on healthcare systems regardless of how much money people had.

4.3.3.2. Synthesis and policy insight

Prior to the pandemic, health expenditure – particularly public spending in Southern Africa – and economic prosperity were key drivers of improved population health across African regions. The strong negative impact of private health expenditure in East Africa contrasted sharply with its positive role in West Africa, revealing structural inequalities and differences in healthcare delivery systems. These divergent effects underscore the importance of a contextualised policy design that aligns healthcare financing models with access, affordability, and health equity. The onset of COVID-19, however, disrupted nearly all established relationships. Across all sub-regions, previously significant predictors of SDG 3 achievement – including GDP per capita, health expenditure, and private-sector financing – lost statistical significance. The finding suggests that the pandemic created an environment where health outcomes were no longer driven by structural investment or economic strength but by emergency responses, systemic strain, and rapid reallocation of resources.

In several regions, coefficients reversed signs or inflated in magnitude without gaining statistical significance. This further confirms the unpredictability introduced by the pandemic and the complex relationship between economic resilience, public health response, and systemic capacity. Importantly, the high coefficient for government health spending in Southern Africa (1.155) and the lack of a negative effect from private spending in East Africa suggest there may be temporary issues with how effective spending is and how it matches up with results. Moving forward, policy strategies should aim to re-anchor health investment on long-term foundations of resilience, equity, and system efficiency. The evidence indicates that governments need to not only restore the losses from the crisis, but also tackle the underlying disparities in healthcare delivery and financing. Restoring the developmental role of economic growth in improving health outcomes will require deliberate planning, especially in light of potential future health shocks. Targeted reforms that integrate public health, economic recovery, and financial protection – particularly in regions like East Africa – are essential to re-accelerate progress toward SDG 3.

4.3.4. ***Model 4:*** *SDG 7 – identifying the factors influencing the achievement of affordable and clean energy*

The regression results presented in Table 13, analysed the determinants of the Affordable and Clean Energy Indicator (lnsdg7) across four subregions of Africa: Central Africa, East Africa, Southern Africa, and West Africa. The model examines the influence of the log of GDP per capita (lngdppc), the log of Population Age (lnpa), the log of Natural Resources Depletion (lnrd), and the log of the Environmental Sustainability Indicator (lnsdg13) on access to affordable and clean energy within each subregion.

Table 13. Estimated results from Model 4: SDG 7 with COVID-19 dynamics, source: Authors' estimation

	CENTRAL AFRICA			EAST AFRICA			SOUTHERN AFRICA			WEST AFRICA		
	AGGRE-GATE	PRE-COVID	DURING-COVID	AGGRE-GATE	PRE-COVID	DURING-COVID	AGGRE-GATE	PRE-COVID	DURING-COVID	AGGRE-GATE	PRE-COVID	DURING-COVID
lngdppc	0.074	0.108	0.448***	0.592***	0.541***	0.366***	0.901***	0.921***	0.782***	0.849***	0.927***	0.621*
	(0.190)	(0.203)	(0.171)	(0.053)	(0.052)	(0.126)	(0.102)	(0.124)	(0.049)	(0.156)	(0.160)	(0.322)
	[0.39]	[0.53]	[2.62]	[11.14]	[10.43]	[2.91]	[8.87]	[7.4]	[16]	[5.43]	[5.8]	[1.93]
lnpa	-0.486	-0.861	0.538	0.175**	0.142*	-0.051	0.804***	0.820**	1.345*	-0.063	-0.27	0.584
	(0.580)	(0.611)	(0.588)	(0.078)	(0.083)	(0.174)	(0.254)	(0.323)	(0.704)	(0.373)	(0.380)	(0.825)
	[-0.84]	[-1.41]	[0.92]	[2.24]	[1.7]	[-0.29]	[3.17]	[2.54]	[1.91]	[-0.17]	[-0.71]	[0.71]
lnsdg13	-0.835	-2.911	2.544	5.996***	5.820***	2.13	5.037***	5.074***	6.619***	-0.114	2.402	2.163
	(2.532)	(2.797)	(1.692)	(2.018)	(2.003)	(2.189)	(1.074)	(1.330)	(2.448)	(6.196)	(6.080)	(11.385)
	[-0.33]	[-1.04]	[1.5]	[2.97]	[2.91]	[0.97]	[0.47]	[3.82]	[2.7]	[-0.02]	[0.4]	[0.19]
lnnrd	-0.042	-0.048	-0.012	0.003	-0.002	0.003	0.032	0.011	-0.024	-0.050***	-0.037**	0.115
	(0.046)	(0.047)	(0.024)	(0.013)	(0.013)	(0.031)	(0.068)	(0.079)	(0.183)	(0.019)	(0.018)	(0.085)
	[-0.91]	[-1.03]	[-0.5]	[0.21]	[-0.15]	[0.11]	[0.47]	[0.14]	[-0.13]	[-2.65]	[-2.06]	[1.34]
_cons	7.368	16.945	-11.708	-28.233	-27.048***	-8.634	-27.431	-27.771***	-34.323***	-2.167	-14.038	-11.8
	(12.680)	(14.002)	(8.466)	(9.472)	(9.409)	(10.549)	(5.789)	(7.208)	(12.178)	(28.994)	(28.452)	(53.355)
	[0.58]	[1.21]	[-1.38]	[-2.98]	[-2.87]	[-0.82]	[-4.74]	[-3.85]	[-2.82]	[-0.07]	[-0.49]	[-0.22]
Obs.	112	98	14	192	168	24	80	70	10	256	224	32
R^2	0.064	0.128	0.020	0.509	0.480	0.003	0.101	0.104	0.288	0.119	0.128	0.008

***, **, * denotes significance levels at 1%, 5%, and 10% respectively. The dependent variables here is the sustainable development goas measured lnSDG7. The random effect estimation was employed in Model 4. The standard errors are in parentheses, while the t-statistics are in braces.

Considering the log of GDP per capita (lngdppc), a positive and statistically significant relationship with the Affordable and Clean Energy Indicator (lnsdg7) is observed in East Africa (0.592, p<0.001), Southern Africa (0.901,

$p<0.001$), and West Africa (0.849, $p<0.001$). This indicates that higher levels of economic development are associated with greater access to affordable and clean energy in these subregions. Central Africa, however, shows a positive but statistically insignificant coefficient (0.074). The policy implication is that economic growth in East, Southern, and West Africa appears to facilitate the adoption and accessibility of cleaner and more affordable energy sources. Policies aimed at fostering economic development in these regions are likely to have positive spillover effects on the energy sector. Central Africa may require targeted interventions beyond general economic growth to improve access to affordable and clean energy.

The log of Population Age (lnpa) exhibits a mixed impact on the Affordable and Clean Energy Indicator (lnsdg7). East Africa (0.175, $p<0.05$) and Southern Africa (0.804, $p<0.001$) show positive and statistically significant coefficients, suggesting that a larger elderly population is associated with greater access to affordable and clean energy in these subregions. This could potentially reflect a greater demand for reliable energy sources or a higher adoption rate of cleaner energy technologies among older demographics in these areas. Conversely, Central Africa (-0.486) and West Africa (-0.063) show negative and statistically insignificant coefficients. The policy implication is that demographic factors play a varying role in energy access across the continent, and energy policies may need to consider the age structure of the population in different subregions.

The log of Natural Resources Depletion (lnrd) shows a statistically significant negative relationship with the Affordable and Clean Energy Indicator (lnsdg7) only in West Africa (-0.050, $p<0.01$). This suggests that higher natural resource depletion in this subregion is associated with reduced access to affordable and clean energy. This could indicate a prioritization of resource extraction over investments in sustainable energy infrastructure or potential environmental degradation hindering clean energy initiatives. Central Africa (-0.042), East Africa (0.003), and Southern Africa (0.032) exhibit statistically insignificant coefficients. The policy implication for West Africa is the need to balance natural resource exploitation with investments in and policies that promote affordable and clean energy sources to ensure long-term energy security and environmental sustainability.

The log of the Environmental Sustainability Indicator (lnsdg13) demonstrates a positive and statistically significant relationship with the Affordable and Clean Energy Indicator (lnsdg7) in East Africa (5.996, $p<0.001$) and Southern Africa (5.037, $p<0.001$). This strong positive association suggests that higher levels of overall environmental sustainability are linked to greater access to affordable and clean energy in these subregions. This likely reflects a synergistic relationship where efforts towards environmental sustainability, such as promoting renewable energy, simultaneously improve access to cleaner energy options. Central Africa (-0.835) and West Africa (-0.114) show negative and statistically insignificant coefficients. The policy implication for East and Southern Africa is to continue fostering environmental sustainability initiatives as they appear to complement efforts to expand access to affordable and clean energy. Central and West Africa may need to identify and address specific barriers that prevent a similar positive synergy between environmental sustainability and clean energy access.

4.3.4.1. Disaggregated assessment of SDG 7 trajectories in Africa: unpacking pre- and during-COVID dynamics

The log of GDP per capita (lngdppc) demonstrated a strong and statistically significant relationship with affordable and clean energy across most African sub-regions before the pandemic. In East Africa (0.541, $p < 0.01$), Southern Africa (0.921, $p < 0.01$), and West Africa (0.927, $p < 0.01$), there was a strong positive link showing that higher economic output helped improve access to affordable and clean energy, likely because it allowed for more investment in clean energy projects and technologies. Central Africa (0.108, ns) exhibited a positive but statistically insignificant relationship. During the pandemic, the positive link with lngdppc continued and even became statistically significant in Central Africa (0.448, $p < 0.01$), suggesting that areas with stronger economies kept up or even sped up their clean energy changes. East Africa (0.366, $p < 0.01$), Southern Africa (0.782, $p < 0.01$), and West Africa (0.621, $p < 0.10$) retained positive and significant coefficients, albeit with slightly reduced magnitudes. These results indicate that GDP per capita remained a reliable enabler of clean energy development even under pandemic conditions, highlighting the fundamental role of economic strength in maintaining energy progress during crises.

The log of population age (lnpa) yielded regionally divergent outcomes before COVID-19. Southern Africa (0.820, $p < 0.05$) and East Africa (0.142, $p < 0.10$) exhibited positive and significant associations with SDG 7, suggesting that ageing populations may be linked to greater energy efficiency, behavioural shifts, or community-driven clean energy adoption. Central Africa (–0.861, ns) and West Africa (–0.270, ns) showed no significant relationship. During the pandemic, the significant associations largely vanished, with the exception of Southern Africa, where the coefficient increased in magnitude and remained significant (1.345, $p < 0.10$). Central Africa (0.538, ns), East Africa (–0.051, ns), and West Africa (0.584, ns) showed statistically insignificant results. The persistence and strengthening of the positive relationship in Southern Africa suggest that demographic patterns in that region may have supported sustained progress in clean energy, possibly through behavioural resilience or targeted community responses among older populations.

The log of environmental sustainability (lnsdg13) showed a strong connection before COVID-19 with SDG 7 in East Africa (5.820, $p < 0.01$) and Southern Africa (5.074, $p < 0.01$), meaning that better environmental sustainability was linked to better access to affordable and clean energy. This is consistent with policy integration efforts and reflects the co-benefits of environmental regulation and clean energy investment. In Central Africa (–2.911, ns) and West Africa (2.403, ns), the relationships were statistically insignificant. During COVID-19, however, the synergy weakened in most regions, with East Africa (2.130, ns) and West Africa (2.163, ns) both yielding insignificant coefficients. Central Africa shifted to a positive but still non-significant association (2.544, ns), while Southern Africa maintained a strong and significant link (6.619, $p < 0.01$). This finding underscores Southern Africa's resilience in maintaining SDG synergies under pandemic strain, possibly due to robust institutional frameworks or integrated policy environments that prioritise clean energy and environmental sustainability together.

The log of natural resource depletion (lnnrd) was mostly not significant in most regions before COVID, except in West Africa, where it had a negative and important link (–0.037, $p < 0.01$), suggesting that more depletion of natural resources made it harder to achieve affordable and clean energy. This likely reflects the difficulties resource-dependent economies face in transitioning away from fossil fuels. Central Africa (–0.048, ns), East Africa (–0.002, ns), and Southern Africa (0.011, ns) exhibited no significant relationships. During the pandemic, lnnrd became insignificant in all regions: Central Africa (–0.012), East Africa (0.003), Southern Africa (–0.024), and West Africa (0.115; all ns). This decline might indicate that the crisis changed the focus of policies away from long-term sustainability issues or temporarily lowered extractive activity, making the depletion variable less important for clean energy results.

4.3.4.2. Synthesis and Policy Insight

Prior to the COVID-19 pandemic, economic prosperity – as measured by GDP per capita – emerged as a consistent and powerful enabler of clean energy access across East, Southern, and West Africa. This finding reinforces the idea that sustained economic growth creates fiscal space for investments in clean infrastructure and renewable technologies. The continued significance of GDP per capita during the pandemic further highlights the structural importance of economic resilience in protecting and advancing energy goals during crises.

Synergies between environmental sustainability (SDG 13) and affordable and clean energy (SDG 7) were also evident pre-COVID, particularly in East and Southern Africa, where integrated environmental and energy policies likely contributed to concurrent progress. However, these synergies weakened during the pandemic, likely due to redirected fiscal priorities, administrative bottlenecks, or the predominance of short-term health and economic concerns. Southern Africa stands out as an exception, maintaining and even enhancing these connections, which may indicate institutional robustness or successful policy continuity under pressure.

Population age (lnpa) displayed region-specific influence, most notably in Southern Africa, where the positive and significant impact both persisted and intensified during the pandemic. This highlights the potential value of demographic awareness in clean energy policy design, particularly in understanding how age-related behavioural patterns or community structures can affect energy transitions. Conversely, the disappearance of the previously significant effect in East Africa points to possible disruptions in community-driven initiatives or generational energy behaviours under crisis conditions.

The significant pre-COVID negative association between natural resource depletion and clean energy in West Africa underscores the structural tension between extractive economies and sustainable energy transitions. The loss of this significance during the pandemic could suggest a temporary suppression of resource exploitation or a policy vacuum that neglects long-term energy strategies in favour of short-term stability. Overall, the COVID-19 pandemic significantly disrupted the dynamics underpinning SDG 7 progress in many African regions. However, the strong impact of GDP per capita and Southern Africa's steady performance in various areas show how important economic strength, good policies, and population factors are for maintaining energy changes, even during major disruptions. Policymakers should thus prioritise green recovery strategies that reinforce these linkages and expand clean energy access through inclusive and regionally tailored interventions. In particular, Southern Africa's resilience offers a model for building institutional continuity and aligning SDG goals in the face of future crises.

4.4. Examining shifts in sustainable development across pre- and post-COVID-19 eras in Sub-Saharan Africa, graphical analysis of health outcomes and sustainable development indicators across the sub-regions

This section graphically presents a comparative analysis of key sustainable development indicators: Sustainable Development Goal 3 (SDG3: Good Health and Well-Being), SDG7 (Affordable and Clean Energy), SDG13 (Climate Action) and Health Expenditure per Capita (HEPC) across four sub-Saharan African regions: Central Africa, East Africa, Southern Africa, and West Africa. The analysis is structured around two distinct temporal phases: the pre-COVID period and the post-COVID period, enabling an assessment of the pandemic's differential impacts on health, energy, and environmental sustainability. We begin our analysis with the average health expenditure per capita.

4.4.1. Analysis of Health Expenditure Per Capita

The bar chart (Figure 1) provides a comparative analysis of the average health expenditure per capita (HEPC) across four sub-Saharan African regions: Central Africa, East Africa, Southern Africa, and West Africa, both before and following the onset of the COVID-19 pandemic. The data is divided into two distinct periods: *pre-*

COVID (indicated by orange bars) and post-COVID (indicated by red bars), facilitating an examination of the pandemic's potential impact on household spending patterns within these regions.

The chart visually demonstrates distinct regional variations in average health expenditure per capita during both periods. Before the pandemic, Southern Africa exhibited the highest average health expenditure, followed by Central Africa, East Africa, and West Africa, which recorded the lowest values. In the post-COVID-19 period, a notable shift is observed in Southern Africa, where the average health expenditure experienced a substantial decrease. In contrast, both East Africa and West Africa showed a modest increase in average HEPC during the post-pandemic period. Central Africa appears to have maintained a relatively stable average HEPC across both periods.

These observations suggest a heterogeneous impact of the COVID-19 pandemic on health expenditure per capita across the sub-Saharan African regions. The significant decline in Southern Africa's average HEPC could be attributed to various factors, such as economic disruptions, job losses, or changes in consumer behaviour specific to this region in response to the pandemic. Conversely, the slight increases observed in East and West Africa might indicate a degree of resilience or different coping mechanisms within these economies. The stability in Central Africa's average HEPC could reflect a more muted impact of the pandemic on health expenditure in this region.

Further rigorous statistical analysis, coupled with socio-economic contextualisation, would be necessary to ascertain the statistical significance of these observed changes and to delve deeper into the underlying drivers of these regional disparities in the impact of the COVID-19 pandemic on household final consumption expenditure.

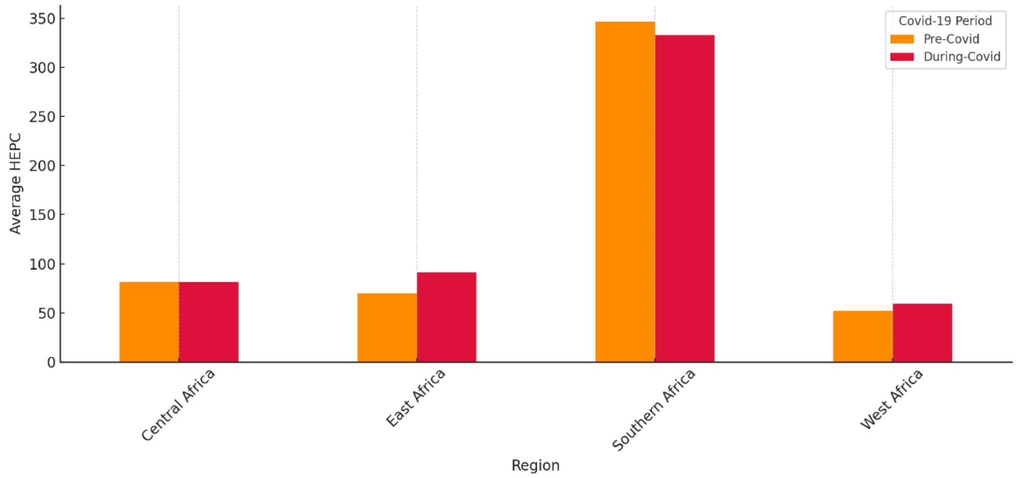

Figure 1. Average HEPC by sub-region: pre-COVID vs during-COVID, source: Authors' compilation

4.4.2. Sustainable Development Goal 3 (Good Health and Well-Being),

Figure 2 presents a comparative analysis of the average Sustainable Development Goal 3 (SDG3) scores, which aim to ensure healthy lives and promote well-being for all ages, across four regions in sub-Saharan Africa. The data is depicted for two distinct periods: *pre-COVID* (indicated by light blue bars) and *post-COVID* (indicated by salmon-pink bars), facilitating an examination of potential changes in health outcomes associated with the COVID-19 pandemic across these regions.

An initial visual inspection of the chart reveals relatively high average SDG3 scores across all four regions in both the pre- and post-COVID-19 periods. This observation suggests that, on average, health outcomes, as measured by the indicators comprising SDG3, were reasonably positive across sub-Saharan Africa both before and after the onset of the pandemic. However, a detailed comparison between the two periods indicates a consistent trend of marginal improvement in the average SDG3 score across all four regions in the post-COVID-19 period. Specifically, Central Africa, East Africa, Southern Africa, and West Africa all demonstrate slightly higher average SDG3 scores in the *post-COVID* period compared to the *pre-COVID* period. Although the magnitude of these increases appears modest, the consistency across all regions warrants further investigation.

This seemingly counterintuitive trend, suggesting an improvement in average health outcomes post-COVID-19, requires careful interpretation. It is essential to consider the specific indicators that constitute the SDG3 composite score and the potential time lags in observing the full impact of the pandemic on various health dimensions. It is possible that certain immediate health indicators, or the methodologies used to assess them, may have exhibited positive trends in the short term, even amidst the broader health challenges posed by the pandemic. Further in-depth analysis, utilizing disaggregated data for the individual components of SDG3 and controlling for other potentially confounding factors, is crucial to provide a more comprehensive understanding of the pandemic's impact on health outcomes in sub-Saharan Africa. Qualitative research exploring the specific health interventions and challenges faced by each region during and after the pandemic would also enhance this quantitative analysis.

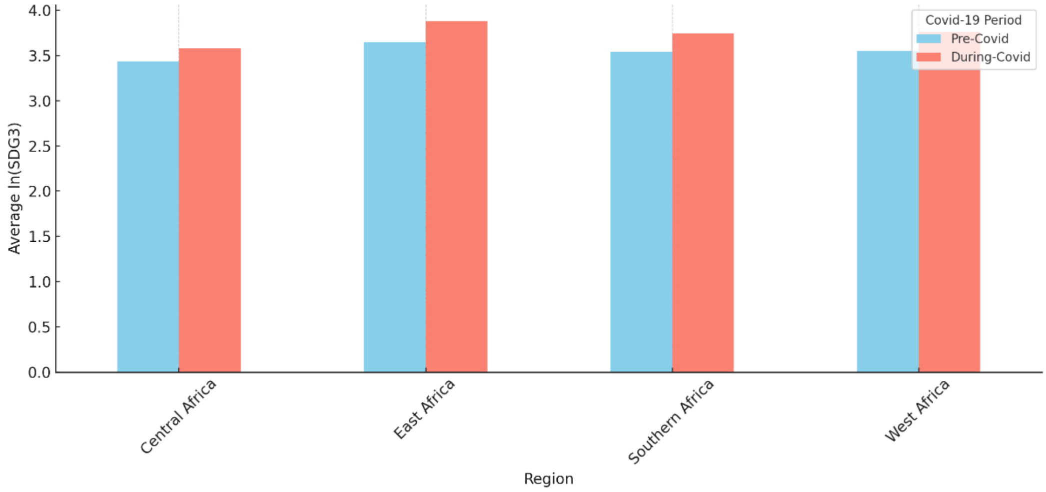

Figure 2. Average SDG 3 score by sub-region: pre-COVID vs during-COVID, source: Authors' compilation

4.4.3. Sustainable Development Goal 7 (Affordable and Clean Energy)

The bar chart provides a comparative analysis of the average Sustainable Development Goal 7 (SDG7) score, which aims to ensure access to affordable, reliable, sustainable, and modern energy for all, across four sub-Saharan African regions: Central Africa, East Africa, Southern Africa, and West Africa. The data is divided into two periods: *pre-COVID* (indicated by light green bars) and *post-COVID* (indicated by orange bars), facilitating an examination of potential changes in energy access and sustainability associated with the COVID-19 pandemic across these regions. A visual assessment reveals generally moderate to high average SDG7 scores across the four regions in both the pre- and post-COVID-19 periods, suggesting a baseline level of progress towards affordable and clean energy access. However, regional variations and temporal shifts warrant closer scrutiny.

In the pre-COVID-19 period, Southern Africa exhibited the highest average SDG7 score, indicating relatively better performance in energy access and sustainability compared to the other regions. Central Africa and East Africa displayed moderately high scores, while West Africa recorded the lowest average SDG7 score among the four regions. Post-COVID-19, a consistent trend of improvement in the average SDG7 score is observed across all four sub-Saharan African regions. Southern Africa maintains its position with the highest average score, showing a further increase. Notably, West Africa demonstrates the most substantial relative increase in its average SDG7 score, although it still lags slightly behind Central and East Africa in the post-pandemic period. Central Africa and East Africa also exhibit positive, albeit smaller, increases in their average SDG7 scores.

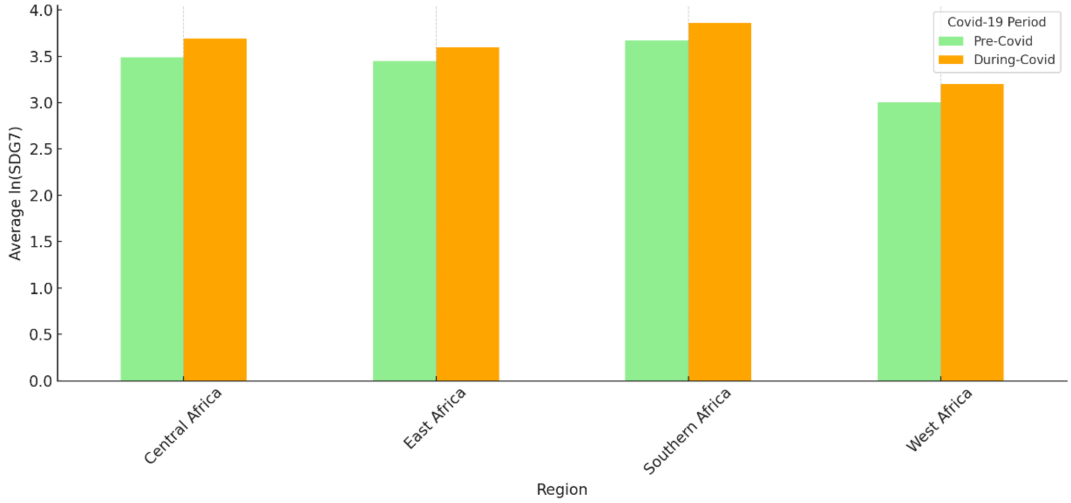

Figure 3. Average SDG 7 score by sub-region: pre-COVID vs during-COVID, source: Authors' compilation

This observed trend of improvement in SDG7 scores across sub-Saharan Africa during the COVID-19 pandemic is noteworthy and potentially counterintuitive given the widespread economic disruptions caused by the pandemic. Several factors could potentially explain this trend. Firstly, the pandemic may have catalysed increased investment and policy focus on sustainable energy solutions as part of recovery efforts or in recognition of the importance of reliable energy access for essential services and economic resilience. Secondly, shifts in economic activity and

industrial output during lockdowns might have temporarily influenced energy consumption patterns and the indicators used to calculate the SDG7 score. Thirdly, international development efforts and aid flows directed towards energy infrastructure and clean energy initiatives may have continued or even accelerated during this period.
However, it is crucial to interpret these findings with caution. The composite nature of the SDG7 score necessitates a deeper analysis of its components (e.g., access to electricity, reliance on clean fuels and technologies, energy efficiency, renewable energy share) to understand which specific aspects drove these improvements. Furthermore, regional variations in policy responses, economic structures, and the specific impacts of the pandemic likely played a significant role in shaping these trends. Future research should focus on disaggregating the SDG7 score, employing econometric analysis to control for confounding factors, and incorporating qualitative data to provide a more nuanced understanding of the relationship between the COVID-19 pandemic and progress towards affordable and clean energy in sub-Saharan Africa. Investigating the sustainability and long-term implications of these observed improvements will also be critical.

4.4.4. Sustainable Development Goal 13 (Climate Action)
The bar chart presents a comparative analysis of the average Sustainable Development Goal 13 (SDG13) score, which focuses on taking urgent action to combat climate change and its impacts, across four sub-Saharan African regions: Central Africa, East Africa, Southern Africa, and West Africa. The data is disaggregated into two periods: *pre-COVID* (represented by light purple bars) and *post-COVID* (represented by tomato-red bars), allowing for an examination of potential shifts in climate action associated with the COVID-19 pandemic across these regions. The chart reveals relatively consistent average SDG13 scores across all four regions and both the pre- and post-COVID-19 periods. This suggests a degree of stability in the indicators contributing to the average assessment of climate action within these sub-Saharan African regions, at least at this level of aggregation.
Specifically, in both the *Pre-COVID* and *Post-COVID* periods, Central Africa, East Africa, Southern Africa, and West Africa exhibit very similar average SDG13 scores. There is a marginal increase observed in the average SDG13 score in the post-COVID-19 period across all four regions. While the magnitude of this increase appears small, its consistency across the different sub-regions warrants consideration. The slight improvement in average SDG13 scores post-COVID-19 could potentially be attributed to several factors. The pandemic led to significant disruptions in economic activity, which may have resulted in temporary reductions in greenhouse gas emissions and related environmental impacts, thus influencing some of the indicators that contribute to the SDG13 score. Furthermore, the pandemic may have heightened global awareness of systemic risks and the interconnectedness of environmental and health crises, potentially leading to increased policy attention or shifts in practices related to climate action. International collaborations and funding mechanisms aimed at climate change mitigation and adaptation may have also continued or evolved during this period.
However, it is crucial to acknowledge the limitations of interpreting these aggregate scores. The SDG13 index comprises a range of indicators related to climate change mitigation, adaptation, impact reduction, and education. A more granular analysis of these individual components would be necessary to understand the specific areas where changes occurred and the underlying drivers of the observed trends. Regional variations in vulnerability to climate change, pre-existing climate policies, and the specific socio-economic impacts of the pandemic likely influenced the trajectory of climate action in each sub-region.

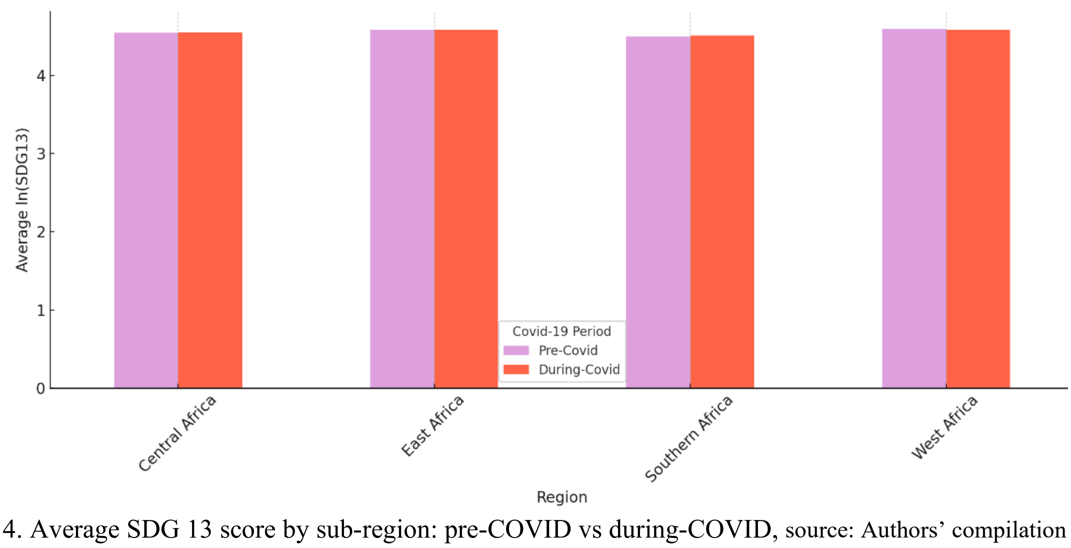

Figure 4. Average SDG 13 score by sub-region: pre-COVID vs during-COVID, source: Authors' compilation

5. Conclusions and policy implications

This study aimed to explore how energy transition, environmental sustainability, and healthcare costs are connected in developing Sub-Saharan African (SSA) countries, with the main goal of understanding how these factors affect the achievement of Sustainable Development Goals (SDGs) 3 (Good Health and Well-being), 7 (Affordable and Clean Energy), and 13 (Climate Action). The research used energy transition theory and Grossman's health production model to analyse data from four regions—Central, East, Southern, and West Africa—looking at how renewable energy use, environmental sustainability, healthcare spending, and health system performance are related through four connected models. The study further extended its empirical scope to compare development trajectories across pre- and during COVID-19 periods, capturing systemic disruptions and resilience patterns using both econometric estimates and graphical data visualisation.

The results from **Model 1** show that using renewable energy helps improve environmental sustainability in Central and East Africa, but in Southern Africa, it seems to have a negative impact, indicating possible problems or side effects from its renewable energy use. GDP per capita negatively affects environmental sustainability in all regions, aligning with the environmental Kuznets curve hypothesis in low-income settings. Population age displays divergent effects, enhancing sustainability in Southern Africa but diminishing it in Central and West Africa. However, the COVID-19 dynamics reveal that the positive pre-pandemic links between renewable energy and sustainability weakened significantly during the crisis, while the negative influence of economic growth persisted, albeit with some regional attenuation. Notably, resource depletion became a more prominent constraint in West Africa during the pandemic, suggesting growing environmental pressure amid recovery efforts. A recovery strategy that reinvigorates clean energy investments, embeds environmental considerations in stimulus programmes, and applies region-specific demographic and resource responses will be critical for accelerating SDG 13 in the post-pandemic era.

In **Model 2**, a robust and negative relationship between renewable energy consumption and health expenditure per capita across most subregions suggests that clean energy investments can help lower pollution-related disease burdens, thus reducing health system costs. GDP per capita positively correlates with health spending, while the impact of population age and resource depletion varies by region. The pandemic significantly disrupted these patterns. While renewable energy previously contributed to lower health costs, its impact became statistically insignificant during the COVID-19 period, possibly due to redirected health spending and the narrowing of health system priorities. Similarly, GDP's association with health expenditure weakened in all regions except East Africa, underscoring the fiscal reallocation and systemic strain induced by the pandemic. These findings reaffirm the co-benefits of clean energy for public health, but they also caution that such benefits may be easily disrupted in crises. Therefore, pandemic-resilient energy policies must be complemented by health financing strategies that maintain environmental and preventive health links under emergency conditions.

Model 3 identifies GDP per capita as a consistent and positive determinant of health outcomes pre-COVID across all subregions, highlighting economic development as a critical enabler of SDG 3. However, total health expenditure did not consistently improve outcomes—particularly in Southern and West Africa—suggesting inefficiencies in resource use. Public spending demonstrated more reliable positive effects, particularly in East and Southern Africa, whereas private spending was beneficial in West Africa but had adverse effects in East Africa. The COVID-19 pandemic disrupted nearly all these relationships. Across all regions, health outcomes became weakly or insignificantly linked to economic strength or expenditure patterns, as governments shifted towards emergency response and resource reallocation. Interestingly, the negative role of private spending in East Africa dissipated, and the positive effect of public spending in Southern Africa persisted with an even larger coefficient. These shifts reflect the structural instability of health systems under crisis and the unpredictable performance of spending efficiency. Policymakers must focus on strengthening system resilience and equity in health financing. Restoring and preserving the developmental impact of economic growth on health will require long-term investment in both infrastructure and institutional efficiency.

Model 4 shows that GDP per capita is a consistently strong driver of affordable and clean energy access in East, Southern, and West Africa. Environmental sustainability also supports SDG 7 outcomes in East and Southern Africa, while natural resource depletion constrains clean energy progress in West Africa. During COVID-19, the economic driver (GDP) retained its significance across all subregions, and in Central Africa, its role became newly significant, suggesting that economically resilient regions sustained or even expanded clean energy investments. Environmental sustainability and demographic drivers (age) lost significance in most regions, except in Southern Africa, where their influence intensified. This trend highlights regional disparities in institutional capacity and policy coherence. The weakening of previously strong SDG synergies in most regions points to pandemic-induced fragmentation in development planning. Southern Africa, however, demonstrates resilience, maintaining and even enhancing key relationships under strain. The evidence suggests that institutional preparedness and integrated policy environments are crucial for buffering clean energy transitions against systemic shocks.

Graphical analyses in section 4.4 further validate these empirical trends. Health expenditure per capita declined post-COVID in Southern Africa, while East and West Africa recorded moderate increases and Central Africa remained stable – revealing uneven fiscal resilience. SDG 3 scores improved marginally across all subregions post-COVID, potentially reflecting short-term gains from targeted interventions or delayed outcome reporting. SDG7 scores improved across all regions, with West Africa experiencing the most notable gains, possibly due to donor-led initiatives and decentralised energy innovations. SDG 13 outcomes remained stable or saw marginal gains, likely due to reduced economic activity rather than proactive climate action.

Collectively, the findings offer important policy-relevant implications for Sub-Saharan Africa's post-pandemic development trajectory. Renewable energy investment emerges as a strategic entry point for achieving dual dividends—advancing climate action while simultaneously alleviating healthcare burdens. As countries design recovery strategies, clean energy infrastructure should be positioned as a high-yield stimulus priority, capable of generating environmental and public health returns. The persistent negative relationship between economic growth and environmental sustainability, particularly during COVID-19, further reinforces the need for green fiscal instruments. Embedding carbon pricing, pollution taxes, and environmentally responsive subsidies into growth models can facilitate the decoupling of economic expansion from ecological degradation.

Equally critical is addressing the inefficiency in health expenditure observed in Southern and West Africa, where increased spending did not translate into improved outcomes. This calls for results-based financing approaches, rigorous performance audits, and a reorientation of public health spending towards measurable access and quality gains. The contrasting effects of private health expenditure across regions also demand nuanced regulatory responses. In East Africa, protections against financial hardship and out-of-pocket health spending are necessary, while in West Africa, targeted support for efficient private healthcare provision may enhance outcomes. Demographic dynamics, particularly population ageing, must be systematically integrated into health and energy policy frameworks. Southern Africa's continued demographic significance during the pandemic demonstrates the value of tailoring interventions to regional age structures and associated consumption patterns. Finally, the pandemic-induced weakening of SDG interlinkages reveals the fragility of sustainability progress in the face of systemic shocks. To mitigate future disruptions, policymakers should prioritise institutional mechanisms that safeguard developmental gains under crisis conditions. Southern Africa's ability to maintain strong synergies between energy, environment, and health during COVID-19 provides a valuable model for resilience, offering insights that can inform regionally adaptive and integrated development strategies across the continent. In sum, this study makes an original contribution by empirically establishing the energy-environment-health nexus in SSA and by demonstrating how crisis periods can both reveal vulnerabilities and highlight pathways for resilient development. Future research should build on these findings by looking at longer periods after the pandemic, combining data from households and institutions, and evaluating how well SDG-aligned interventions are being carried out. As SSA economies rebuild, aligning economic recovery with integrated, multi-sectoral policy frameworks will be critical for sustaining progress towards SDGs 3, 7, and 13.

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