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Africa's Energy Matrix: A Review of Transition Drivers toward Sustainable Electrification

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Abstract

Africa constitutes 17% of the global population yet accounts for only 6% of global energy consumption. With over 600 million without access to electricity and over 900 million relying on biomass for cooking. This paper analyses Africa's transition drivers and electrification pathways. It evaluates Africa's energy mix including biomass, fossil fuels, hydropower, and renewables. It assesses the financing, utility-performance, policy and demographic barriers that produce divergent energy transition trajectories across the continent. It evaluates the transformative role of off-grid and mini-grid solutions in closing the access gap while critically examining whether these technologies serve as a bridge to grid connection or risk becoming a permanent second-tier energy system. The analysis further addresses the climate-equity paradox confronting Africa: negligible emissions yet disproportionate climate vulnerability, and the tension between fossil fuel development and global decarbonization. A comparative assessment of energy strategies identifies transferable lessons on procurement design, market architecture, and political economy. The review concludes that Africa possesses the resource endowments and increasingly the technology to achieve universal energy access; the binding constraints are political commitment to utility reform, financial instruments to de-risk private investment at scale, and an international climate framework that recognizes Africa's right to energy-led development.

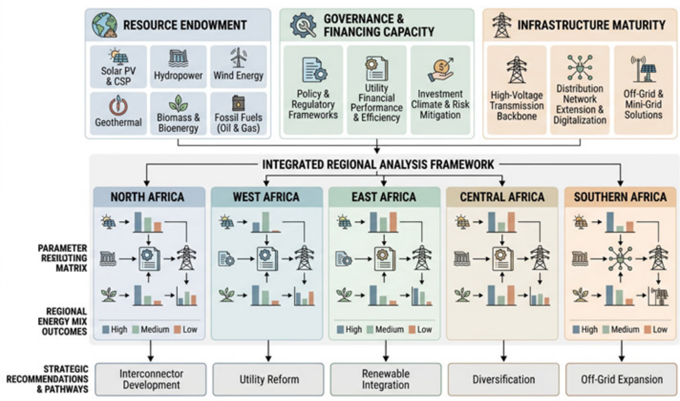
Keywords: ***Energy mix, Africa, renewable energy, electrification, energy transition, off-grid solar, regional power pools, energy policy***

Introduction and Background

Africa's energy matrix comprises a contradiction of plenty and deprivation (Yuan et al., 2026). The plentiful energy potential is constrained by deprivation in technological development to benefit from the vast energy resources (Guruswamy 2024). Africa comprises 60% of the world's solar resources given its strategic tropical location, the largest untapped hydropower potential, significant geothermal resources concentrated along the East African Rift, and emerging wind corridors across North Africa and the Horn of Africa (Ebhota & Inambao, 2016). Yet Africa accounts for only 3% of global electricity consumption and hosts the world's lowest electrification rates, with sub-Saharan Africa's average electricity access is about 50% (Peters et al., 2024).

This contrast of resource wealth and energy poverty makes Africa's energy matrix not merely a technical question of generation portfolios, but a development challenge with profound implications for economic growth, human welfare, and global climate outcomes (Mutumba et al 2021). Africa is endowed with vast energy resources yet is greatly deprived, with energy poverty, lack of access to affordable clean energy. It has barriers to transitioning to clean energy development that greatly constrains it from achieving its development agenda. The analytical framework in figure one illustrates the energy matric for the continent.

Figure 1: Analytical framework for evaluating Africa's energy mix



Source: Schwerhoff, G., & Sy, M. (2019). Developing Africa's energy mix. Climate Policy, 19(1), 108–124. https://doi.org/10.1080/14693062.2018.1459293

The review addresses five core questions. First, how has Africa's energy mix evolved over the past decade, and what are the trends in the composition of primary energy supply and electricity generation? Second, what drives the divergent energy transition pathways across the continent's five sub-regions North, West, East, Central, and Southern Africa? Third, what role do off-grid and mini-grid solutions play in closing the electricity access gap, and what are the limitations of these technologies? Fourth, how do Africa's energy choices interact with climate commitments, particularly regarding the tension between natural gas development and decarbonization? Fifth, what comparative lessons emerge from national energy strategies and regional power pools for the design of effective energy policy?

This paper seeks to analyse the drivers and barriers of Africa's energy transition. Whereas earlier studies have been able to focus of barriers few have been able to address governance and regulatory drivers of energy transition on the continent. The survey synthesizes evidence from the energy-growth nexus literature, African energy studies, and policy analyses, drawing on meta-analytic reviews (Menegaki, 2014; Stanley & Jarrell, 2005), regional energy assessments (Ebhota & Inambao, 2016; Schiffer, 2020), and country-level empirical studies (Adewuyi & Awodumi, 2020; Eldowma et al., 2023). This paper provides an overview of Africa's energy matrix.

The Background of Africa's Energy Matrix

Africa's energy mix has undergone a progressive transformation over the past decade, shifting from traditional-biomass dominance through fossil-fuel expansion toward a modern-renewable diversification. However, the pace and composition of this transition vary starkly across the continent's five sub-regions, reflecting the interplay of resource endowments, investment flows, and policy priorities (Ebhota & Inambao, 2016).

The continent's total primary energy supply (TPES) reached approximately 830 million tonnes of oil equivalent in 2023, with biomass accounting for roughly 45% of the total in sub-Saharan Africa, fossil fuels contributing approximately 40%, and modern renewables predominantly hydropower supplying the remainder. This aggregate picture, however, masks substantial sub-regional heterogeneity. North Africa's energy mix is dominated by natural gas and oil, reflecting the region's hydrocarbon endowments and historical investment patterns. Sub-Saharan Africa, by contrast, remains heavily dependent on traditional biomass, with some countries deriving over 80% of their primary energy from fuelwood, charcoal, and agricultural residues.

Traditional Biomass and the Persistent Cooking Energy Challenge
Traditional biomass including fuelwood, charcoal, agricultural residues, and animal dung remains the dominant primary energy source for over 600 million Africans, primarily for cooking. Despite decades of intervention programs, clean cooking alternatives remain unaffordable and supply chains underdeveloped for the poorest households (Rosenthal et al., 2018). The biomass-energy ladder hypothesis, which posits that households transition to cleaner fuels as incomes rise, has found limited empirical support in African contexts. Instead, evidence suggests that households often stack multiple fuels using both charcoal and LPG, for example rather than making discrete transitions between energy sources.

The externalities of biomass dependence are severe. Indoor air pollution leads to both health and environmental hazards that impact adversely to sustainable development (Niza et al., 2023). Household air pollution from solid fuel combustion causes an estimated 500,000 premature deaths annually in Africa, with women and children disproportionately affected. The environmental costs are equally significant: charcoal production drives deforestation at rates that exceed sustainable yields in many regions, particularly in the peri-urban zones surrounding rapidly growing cities. Improved cookstove programs have achieved limited success, with adoption rates often falling below 20% within two years of distribution. The persistence of biomass dependence reflects a fundamental economic reality. For instance in Uganda 88% of the energy mix is on biomass with a dominating 78% on fuelwood, 5.6% on charcoal and another 4 % on crop waste and dung (Bongomin & Nziu 2022). This is enshrined in clean cooking fuels like LPG, electricity, ethanol remain expensive for households in the lowest income quintiles, and the supply chains required for reliable fuel delivery are underdeveloped across much of rural Africa (Rosenthal et al., 2018). Addressing the clean cooking challenge requires a distinct policy framework that integrates affordability subsidies, fuel supply chain development, and behavior-change interventions sensitive to local cooking practices and cultural preferences.

Fossil Fuels: Oil, Coal, and the Natural Gas Pivot

Fossil fuels account for roughly 40% of Africa's TPES, but their economic significance is concentrated in a handful of producer states and remains largely export-oriented, creating a structural disconnect between hydrocarbon wealth and domestic electrification outcomes (Adewuyi & Awodumi, 2020). Nigeria and Angola are the continent's largest oil producers, with Nigeria's production historically exceeding 2 million barrels per day, yet both countries have electrification rates below 60%. This paradox of oil-rich nations with energy-poor populations reflects the export-oriented structure of Africa's hydrocarbon industry, where crude oil and natural gas are primarily shipped to international markets rather than processed domestically for power generation. South Africa represents the continent's most coal-dependent economy, with coal supplying over 70% of the country's electricity and underpinning its industrial base. With only 2 nuclear reactors, coal lock-in presents a formidable just-transition challenge (Mutumba 2022). Rapid decarbonization of the power sector would disrupt the livelihoods of approximately 90,000 coal miners and the communities dependent on coal-related economic activity. Yet a clear transition road map is key for the continent to realize it sustainable development agenda.

The emerging natural gas frontier spanning Mozambique's Rovuma Basin, Tanzania's offshore discoveries, Senegal's Greater Tortue Ahmeyim project, and Egypt's Zohr field has generated expectations of a gas-to-power transition across the continent. However, the development timelines for these projects have been extended by financing challenges, security concerns in northern Mozambique, and the growing competitiveness of renewables, which increasingly undercut gas on a levelized cost basis for power generation. The stranded-asset risk for African fossil fuel infrastructure is intensifying as global decarbonization accelerates and international financial institutions restrict fossil fuel lending (Harris, 2019). African governments face a narrowing window for monetizing hydrocarbon resources before the global energy transition reduces demand and prices.

Hydropower: The Continent's Largest Renewable Electricity Source

Hydropower supplies over 60% of Africa's renewable electricity, with major installations concentrated along the Nile (Ethiopia's Grand Ethiopian Renaissance Dam, Egypt's Aswan High Dam), Congo (the Inga complex), and Zambezi (Kariba, Cahora Bassa) river systems. The continent's technically exploitable hydropower potential is estimated at 1,750 TWh per year, of which only approximately 10% has been developed. The pipeline of large-dam projects includes the GERD (6,450 MW), the Inga III expansion (4,800 MW proposed), and numerous smaller projects across the East African Rift.

However, hydropower faces a dual threat from climate-induced hydrological variability and growing opposition to large-dam externalities. The near-shutdown of the Kariba Dam in 2019–2022, when water levels fell to less than 1% of usable storage due to successive drought years, exposed the vulnerability of hydropower-dependent systems to climate variability. The GERD's filling negotiations between Ethiopia, Egypt, and Sudan illustrate the geopolitical complexities of transboundary hydropower development (Eldowma et al., 2023). The environmental and social displacement costs of large dams including the displacement of communities, disruption of riverine ecosystems, and sedimentation that reduces reservoir capacity have generated increasing opposition from civil society and international environmental organizations. These constraints suggest that while hydropower will remain a significant component of Africa's electricity mix, its future expansion will be more contested and climate-constrained than historical development patterns would suggest.

Solar, Wind, and Geothermal: The New Growth Frontier

Solar PV has emerged as the fastest-growing energy technology in Africa, with installed capacity growing over 50-fold since 2015, led by South Africa, Egypt, Morocco, and Kenya. Solar PV has overtaken hydropower as the primary source of new renewable capacity additions in Africa since 2020, though its contribution to total generation lags behind capacity due to low capacity factors and grid integration bottlenecks (Hassan et al., 2024). The deployment models span a spectrum from utility-scale independent power producer (IPP) projects like South Africa's Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) has procured over 6,000 MW of renewable capacity since 2011 to commercial and industrial (C&I) rooftop installations and PAYG solar home systems that serve households beyond the grid frontier.

Wind energy is geographically concentrated in specific corridors: North Africa's Mediterranean and Atlantic coasts (Morocco, Egypt), the Horn of Africa (Kenya's Lake Turkana wind farm, the largest in Africa at 310 MW), and South Africa's coastal zones. Geothermal energy is uniquely concentrated along the East African Rift, where Kenya has established itself as the continental leader with over 900 MW of installed capacity and plans to reach 5,000 MW by 2030. Ethiopia, Djibouti, and Tanzania are also developing geothermal resources along the Rift, though at a slower pace.

The rapid growth of solar and wind has been enabled by several converging factors: the dramatic decline in PV module costs driven by Chinese manufacturing scale, the emergence of battery storage that partially addresses intermittency, and the increasing availability of concessional climate finance for renewable energy projects. However, variable renewable energy integration faces significant barriers in African contexts. Most national grids were designed for centralized, dispatchable generation and lack the transmission infrastructure, ancillary services, and market mechanisms required for high renewable penetration. The grid integration challenge is particularly acute in smaller economies where the grid's capacity to absorb variable generation is limited by the size of the synchronous zone.

Table 1: Composition of Africa's energy mix by source, 2015–2025

Energy source	Share of TPES (%)	Installed capacity (GW)	Growth rate (2015–2025)	Regional concentration
Traditional biomass	45	—	Declining slowly	Sub-Saharan Africa
Oil	22	—	Stable	North, West Africa
Natural gas	15	—	Growing	North, East Africa
Coal	3	48	Stable	Southern Africa
Hydropower	10	38	Moderate	East, Central Africa
Solar PV	2	25	>50-fold	North, Southern Africa
Wind	1	9	5-fold	North, East Africa
Geothermal	<1	2	3-fold	East African Rift

Source: World Bank Statistics (2026)

Table 1 summarizes the composition and evolution of Africa's energy mix across major sources. The data reveal a progressive shift from traditional biomass dominance toward solar-led diversification, though the pace of this transition varies substantially across sub-regions.

The significance of this paper

This paper is important due to it novelty in analysing Africa's energy matrix that has intensified over the past decade as three converging forces reshape the continent's energy landscape. First, the cost of solar photovoltaic technology has declined by over 80% since 2010, fundamentally altering the economics of rural electrification and enabling the emergence of pay-as-you-go (PAYG) solar home systems that have connected over 100 million Africans to basic electricity services (Alinda et al 2021).

Second, Africa's demographic trajectory with a population projected to double to 2.5 billion by 2050 and urban populations growing at 3.5% annually makes energy consumption growth the fastest of any continent. Third, the global climate regime increasingly pressures African nations to adopt low-carbon development pathways while simultaneously constraining the international financing available for fossil fuel infrastructure. These intersecting forces create both unprecedented opportunities and formidable challenges for shaping Africa's energy future.

Third it evaluates the role of energy transition in promoting the current development agenda. Despite that the current sustainable development goal 7 emphasizes increasing access affordable clean energy for all. Energy transition, quality and security also important for long term growth. This paper interrogates the transition drivers and barriers for Africa.

Finally it addresses the methodological gap by applying an evaluation framework to systematically interpret Africa's energy matrix across three analytical dimensions: resource availability, governance and financing capacity, and grid-readiness. As illustrated in Figure 1, the framework recognizes that identical energy resources produce divergent outcomes depending on the institutional and infrastructural context in which they are deployed. A solar resource in Kenya, embedded in a policy environment with feed-in tariffs and a relatively functional utility, follows a different deployment trajectory than the same resource in a country with utility insolvency and regulatory uncertainty.

Studies of energy mix in Africa have been done (Schwerhoff, & Sy, 2018, Akrofi, 2021, Oghenekaro, & Kant, 2022).), however, the concept of energy transition in Africa has not been fully studied, this paper focuses on transition barriers and drivers. Drivers and barriers to clean energy transition have useful implications for the energy matric of the entire continent.Empirical literature does not assign responsibility to the key barriers and drivers of Africa's energy mix, this study goes ahead, to highlight the contemporary issues with respect to the transition drivers that is helpful in informing social and economic planner and policy analysts to enable them solve the leading energy challenges of the continent.

The analysis is organized as follows. Section 2 catalogs the drivers and barriers shaping sub-regional energy transitions. Section 3 evaluates the role of off-grid solutions and the electrification frontier. Section 3 addresses climate implications and sustainability. Section 4 provides a comparative analysis of national strategies and regional power pools. Section 5concludes with policy recommendations and a forward-looking research agenda

Findings and Analysis

Drivers and Barriers to Energy Transition in Africa

The drivers of demography, urbanization, and falling renewable technology costs are accelerating energy transitions in Africa's sub-regions, but the pace is constrained by three interacting barriers financing scarcity, utility insolvency, and policy uncertainty whose relative importance differs markedly across the five sub-regions (Espoir et al., 2024; Khobai et al., 2021). Table 2 maps the key barriers to energy transition across the five sub-regions. Africa's energy transition is not a single narrative but a patchwork of sub-regional trajectories shaped by distinct resource endowments, governance structures, and geopolitical contexts.

North Africa leverages its gas wealth and solar resources for an export-oriented transition, with Morocco and Egypt positioning themselves as renewable energy hubs supplying European markets through interconnectors. West Africa grapples with the gas-to-power agenda amid rapid urbanization, with Nigeria's electricity sector reform and the West African Gas Pipeline representing attempts to monetize regional gas resources for domestic power generation. East Africa pioneers geothermal development and regional power trade through the East African Power Pool, with Kenya and Ethiopia emerging as regional generation hubs. Central Africa presents the paradox of abundant hydropower potential the Congo River alone holds an estimated 100 GW of hydropower capacity and the lowest electrification rates on the continent. Southern Africa navigates coal lock-in and the just transition, with South Africa's experience serving as both a cautionary tale and a laboratory for managing the socio-economic dimensions of decarbonization.

This shows efforts of Africa to transition, though for individual countries in the Sub Saharan Africa is a remarkable lag to the transition and access to affordable energy.

The Financing and Investment Gap

Sub-Saharan Africa's annual clean energy investment of approximately $20 billion needs to triple to meet SDG 7 targets. Africa's energy financing gap is primarily a cost-of-capital problem, not a capital-availability problem: political and currency risks inflate the weighted average cost of capital to levels that render otherwise viable renewable projects uneconomic (Sun et al., 2019). African renewable energy projects face financing costs 2–3 times higher than equivalent projects in Europe or North America, with the cost of debt typically ranging from 8–12% compared to 2–4% in developed markets (Lartey 2024).

The investment architecture is dominated by development finance institutions (DFIs), the World Bank, African Development Bank, and European bilateral DFIs which provide concessional loans, guarantees, and technical assistance that crowd in private capital. However, DFI resources alone are insufficient to close the financing gap. Private capital, while increasingly interested in African energy markets, remains constrained by perceived political risk, currency convertibility concerns, and the small scale of individual projects relative to institutional investors' minimum ticket sizes. Chinese lending under the Belt and Road Initiative has been a significant source of energy infrastructure finance, particularly for large hydropower and coal projects, though Chinese energy lending has declined since 2017 as Beijing has shifted toward greener investment criteria. Climate finance instruments like green bonds, carbon credits, and Just Energy Transition Partnerships represent a nascent but growing source of energy finance, though their scale remains orders of magnitude below the investment required.

Table 2: Key barriers to energy transition by sub-region

Sub-region	Primary barrier	Manifestation	Policy priority
North Africa	Policy uncertainty	State-dominated markets, regulatory opacity	Market liberalization
West Africa	Utility insolvency	Below-cost tariffs, high losses, weak collection	Tariff reform, utility restructuring
East Africa	Financing scarcity	High cost of capital, currency risk	De-risking instruments, regional integration
Central Africa	Infrastructure deficit	Minimal grid coverage, weak institutions	Grid extension, institutional capacity building
Southern Africa	Coal lock-in	Employment dependency, vested interests	Just transition planning, economic diversification

Utility Performance and Grid-Readiness Constraints

The financial fragility of African state-owned utilities are driven by below-cost tariffs, high losses, and political interference is the single largest structural barrier to grid-based electrification and renewable energy integration (Gassner & Pushak, 2014). Most utilities are also too old and in a state of disrepair. For instance, Uganda's national grid was established in 1954 and has undergone minimal transformation often leading to power outages even when power supply exceeds peak electricity demand (Mutumba et al 2024).

Most African utilities operate at a financial loss, with quasi-fiscal deficits averaging 1.5% of GDP across the continent. The utility death spiral is well-documented: tariffs set below cost-recovery levels (often for political reasons) erode revenues, limiting investment in maintenance and expansion; deteriorating service quality reduces customers' willingness to pay; and high technical and commercial losses often exceeding 20% of generated electricity further undermine financial viability.

The introduction of IPPs has partially bypassed the utility constraint by enabling private generation under long-term power purchase agreements, with South Africa's REIPPPP serving as the most successful model. However, IPPs depend on the utility as the off taker, and when the utility is financially distressed as is the case with Eskom in South Africa and numerous utilities across the continent the IPP model's sustainability is threatened. The emerging role of distributed energy resources like rooftop solar, battery storage, and microgrids offers a potential pathway that circumvents dysfunctional utilities entirely, but also raises concerns about grid defection by the wealthiest customers, which would further erode the utility revenue base and undermine the cross-subsidization model that supports grid access for poorer households.

Policy Frameworks and Regional Governance Divergence

Sub-regional policy divergence produces a natural experiment: East Africa's coordinated regional approach has delivered faster electrification gains than West Africa's fragmented national strategies, holding resource endowments constant (Akinyemi et al., 2019). The policy environments across sub-regions reflect different governance traditions and political economy configurations. North Africa's state-led renewable procurement, exemplified by Morocco's Noor solar complex and Egypt's Benban solar park, has achieved scale through centralized planning and sovereign guarantees. East Africa's feed-in tariff experiments and regional power pool coordination have fostered a more decentralized, market-oriented approach. West Africa's ECOWAS renewable energy policy framework provides a regional coordination mechanism, but implementation has been uneven across member states.

The effectiveness of national renewable energy targets now adopted by over 40 African countries depends less on the ambition of the targets themselves than on the credibility of the policy instruments deployed to achieve them. Competitive procurement programs, such as South Africa's REIPPPP, have consistently outperformed feed-in tariffs and administrative allocation in delivering renewable capacity at competitive prices. The political economy of fuel subsidy reform remains a critical lever for redirecting fiscal resources from fossil fuel consumption to clean energy investment. Fuel subsidies in Africa cost an estimated $50 billion annually approximately 2% of continental GDP and disproportionately benefit wealthier households. However, reform attempts have been politically fraught, as demonstrated by the protests triggered by subsidy reduction in Nigeria, Sudan, and several other countries.

Demographic Pressures and Urbanization Dynamics

Africa's population is projected to reach 2.5 billion by 2050, with urban populations growing at 3.5% annually (Guengant and May 2013). This demographic trajectory creates a dual energy challenge: rapidly growing urban electricity demand and persistent rural biomass dependence, requiring parallel investment in centralized grid infrastructure and decentralized off-grid solutions (Wang et al., 2024). The urban energy transition is well underway in Africa's largest cities, where rising incomes drive demand for modern energy services like air conditioning, refrigeration, and digital connectivity that require reliable electricity supply. Urban households are increasingly connected to the grid, though connection rates mask significant quality-of-service deficits, with many connected households experiencing frequent outages and voltage fluctuations.

The rural energy challenge is fundamentally different. Rural populations, which account for approximately 60% of Africa's total, remain predominantly dependent on traditional biomass for cooking and heating, and lack access to electricity. The rural-urban energy divide is not merely a function of income differences but reflects the economics of grid extension: the cost of extending the grid to low-density rural settlements is often prohibitive, and the revenue from those connections given low rural incomes and consumption levels is insufficient to recover the investment. This economic reality has driven the emergence of off-grid solutions as the primary mode of rural electrification in many African countries, a topic examined in detail in the following section.

Energy Access, Off-Grid Solutions, and the Electrification Frontier

Off-grid and mini-grid solutions have transformed the economics of rural electrification in Africa, but their long-term developmental impact depends on whether they serve as a bridge to higher-tier grid access or become a permanent, lower-quality substitute for grid infrastructure (Adeleye et al., 2020; Sun et al., 2019). Approximately 600 million Africans lack electricity access, concentrated in the rural areas of sub-Saharan Africa. The traditional electrification paradigm exclusive reliance on grid extension has proven inadequate to the scale of the access challenge. Grid extension rates have consistently lagged behind population growth in many sub-Saharan African countries, meaning that the absolute number of people without electricity access has actually increased in some countries over the past decade.

The emerging electrification paradigm adopts a portfolio approach that integrates grid densification, mini-grids, and standalone solar home systems. This approach recognizes that the optimal technology varies by population density, distance from the existing grid, and household income levels. Grid extension remains the most cost-effective solution for high-density urban and peri-urban areas. Mini-grids are economically optimal for medium-density settlements beyond the grid frontier. Standalone solar systems serve the lowest-density, most remote households.

The PAYG Solar Home System Revolution

PAYG solar has achieved scale by solving the consumer-finance problem for off-grid households, but the technology ceiling of Tier 1–2 access limits its capacity to support productive economic uses beyond basic lighting and communication. Pay-as-you-go solar has connected over 100 million Africans to basic electricity services since 2015, leveraging mobile money platforms and falling PV costs. East Africa hosts over 60% of the global PAYG market, with Kenya, Uganda, and Tanzania as the leading markets, followed by Nigeria in West Africa.

The business model innovation is deceptively simple: households pay a small upfront deposit for a solar home system and then make daily or weekly payments via mobile money over a 12–36-month period, after which they own the system outright. The mobile money infrastructure particularly M-Pesa in East Africa has been the critical enabler, providing a payment platform that eliminates the transaction costs of cash collection. The welfare impacts of PAYG solar are well-documented: households report improved lighting for children's education, reduced expenditure on kerosene and batteries, and increased perception of safety. However, the evidence on productive uses income-generating activities beyond phone charging is thinner. PAYG systems typically provide Tier 1–2 access (basic lighting and phone charging), which is insufficient to power appliances such as refrigerators, sewing machines, or agricultural processing equipment that could generate income and accelerate economic development.

Mini-Grids as the Missing link

Mini-grids are economically optimal for serving approximately 30% of Africa's unelectrified population, but their deployment at scale requires regulatory frameworks that credibly manage grid-arrival risk and permit cost-reflective tariffs. Mini-grids are positioned between standalone solar systems and grid extension, offering higher-tier service for rural communities beyond the grid frontier. The technology has benefited from declining cost curves a 40% reduction since 2018 driven by falling PV and battery costs and standardization of mini-grid design.

The regulatory innovations that have enabled mini-grid deployment include Tanzania's mini-grid framework, which provides a clear licensing regime and tariff-setting methodology, and Nigeria's rural electrification strategy, which has deployed over $500 million in mini-grid funding. However, the single largest barrier to private investment in mini-grids is grid-arrival risk: the uncertainty that discourages investment when the main grid may eventually reach the same community and either undercut the mini-grid on price or render the investment stranded. Credible regulatory frameworks that specify compensation mechanisms for grid arrival or that designate areas where the grid will not reach within a specified timeframe are essential for unlocking private investment at scale.

Grid Extension, Densification and the Quality-of-Service Gap

Grid extension without complementary investment in generation capacity and distribution reliability produces electrification without electricity a measurement problem that inflates official access statistics while masking the quality-of-service deficit. Grid extension remains the dominant mode of electrification, but connection rates lag behind grid reach. The barriers to last-mile connection include high connection charges often $100–500 per household, representing several months of income for poor households' bureaucratic hurdles in obtaining connections, and the quality-of-service gap: many connected households receive unreliable power with frequent outages.

The impact of output-based aid and connection subsidies has been positive but modest. Prepaid metering has improved utility revenue collection in some contexts, but its effectiveness depends on the underlying tariff structure remaining cost-reflective. The emerging threat of grid defection as wealthier customers adopt solar-plus-storage systems to insure against unreliable grid supply poses a systemic risk to the utility business model. Grid defection by high-consumption customers erodes the revenue base that supports the cross-subsidies necessary for grid access for poorer households, potentially accelerating the utility death spiral.

Clean Cooking: The Overlooked Access Dimension

Clean cooking has received a fraction of the policy attention and investment devoted to electricity access, despite accounting for a larger share of Africa's energy-related premature mortality, and requires a distinct policy framework that addresses affordability, cultural preferences, and fuel supply chains (Rosenthal et al., 2018). Clean cooking access has been the neglected dimension of SDG 7 in Africa, with over 900 million people lacking access to clean cooking fuels and technologies. The health burden of household air pollution from solid fuel combustion estimated at 500,000 premature deaths annually in Africa exceeds the mortality from malaria, tuberculosis, and HIV/AIDS combined in some countries.

The limited success of intervention programs reflects the multidimensional nature of the clean cooking challenge. Improved cookstove programs have struggled with low adoption rates, as the stoves often fail to meet user expectations for cooking speed, fuel flexibility, and compatibility with traditional cooking practices. LPG adoption has been constrained by affordability the upfront cost of cylinders and stoves, and the ongoing cost of fuel refills and by supply chain reliability in rural areas. Electric cooking, enabled by the expansion of electricity access, represents a potentially transformative solution, but its feasibility depends on the reliability of electricity supply and the affordability of appliances. Biogas and ethanol have shown promise in specific contexts biogas in agricultural communities with livestock, ethanol in countries with sugar industries but have not achieved scale. Figure 2 illustrates the three electrification pathways, while Table 3 provides a quantitative comparison of their key performance characteristics.

Figure 2: Comparison of off-grid electrification technologies

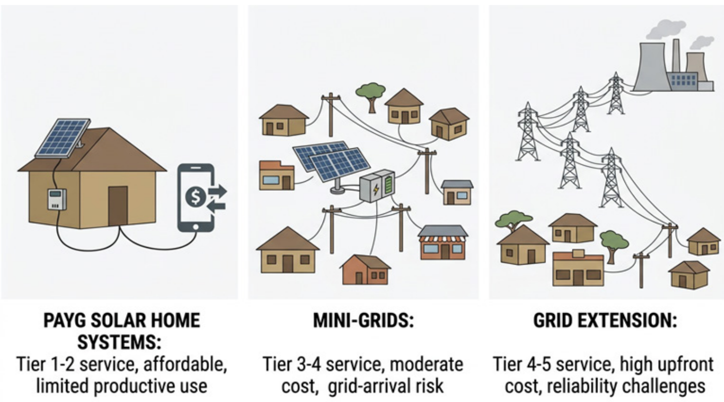


Table 3: Performance comparison of electrification technologies in Africa

Technology	Service tier	Connection cost (USD)	Scalability	Primary market
Grid extension	4–5	500–1,500	High (urban)	Urban, peri-urban
Mini-grid	3–4	200–800	Medium	Rural towns
PAYG solar home system	1–2	50–200	High (rural)	Remote rural

Climate Implications and the Sustainability of Africa's Energy Choices

Africa's energy transition presents a paradox of global equity: the continent's contribution to cumulative emissions is negligible, yet its energy choices over the next decade particularly whether natural gas serves as a bridge fuel or a lock-in will materially influence the feasibility of the 1.5C target (Harris, 2019; Schwerhoff & Sy, 2018). Africa contributes less than 4% of global cumulative CO2 emissions, yet faces disproportionate climate impacts that threaten energy system reliability. Hydropower output is sensitive to changing rainfall patterns, thermal power plants require cooling water that may become scarce, and coastal energy infrastructure faces sea-level rise and intensifying storm surges.

The tension between Africa's development imperative and global decarbonization pressure is acute. African per capita electricity consumption averages approximately 500 kWh per year less than one-tenth of the European average and one-twentieth of the North American average. The energy required to industrialize, to power hospitals and schools, to refrigerate vaccines, and to enable digital connectivity is substantial. Demanding that Africa forgo fossil fuel development while the continent's historical contribution to climate change is negligible raises profound questions of climate justice.

National Climate Commitments and the Fossil Fuel Dilemma

African governments face a prisoner's dilemma: individually rational fossil fuel development undermines the collective climate outcome, yet the absence of a credible mechanism to compensate foregone fossil fuel revenues makes unilateral decarbonization politically untenable. The Nationally Determined Contributions (NDCs) submitted by African countries under the Paris Agreement reveal a significant ambition gap: conditional pledges dependent on external finance would reduce emissions, but unconditional pledges are largely consistent with business-as-usual trajectories.

The political economy of the "gas as transition fuel" debate is particularly salient in the cases of Senegal and Mozambique, where major gas discoveries are being developed. For Senegal, the Greater Tortue Ahmeyim project promises export revenues that could transform the country's fiscal position. For Mozambique, the Rovuma Basin represents one of the largest gas discoveries globally, but development has been delayed by the insurgency in Cabo Delgado province. The tension between export revenue maximization and domestic decarbonization reflects a broader pattern: African fossil fuel development is primarily driven by export markets, not domestic energy needs, and the revenues generated are often concentrated in sovereign wealth funds or government budgets rather than invested in domestic energy access.

Critical Minerals and the Clean Energy Supply Chain

Africa's role in the global clean energy supply chain reproduces a colonial extraction pattern raw materials exported, value added elsewhere unless accompanied by industrial policy that mandates domestic processing and beneficiation. Africa hosts significant reserves of minerals essential for clean energy technologies: cobalt (DRC, 70% of global supply), lithium (Zimbabwe), graphite (Mozambique, Tanzania), and rare earth elements. The environmental and social costs of extraction including artisanal cobalt mining in the DRC, which involves child labor and hazardous working conditions have generated international scrutiny and supply-chain due diligence regulations in the EU and US.

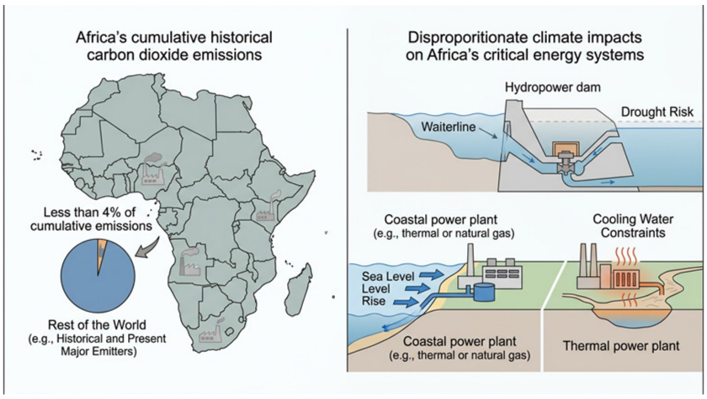
The resource curse risks are well-documented in the African context: mineral wealth can fuel corruption, exacerbate inequality, and crowd out other sectors of the economy through exchange rate appreciation. The limited domestic value addition most African minerals are exported as raw ores or concentrates, with processing and manufacturing concentrated in China means that the economic benefits of the clean energy transition accrue disproportionately to downstream economies. Industrial policy that mandates domestic processing and beneficiation, coupled with governance reforms that ensure mineral revenues are transparently managed and invested in domestic energy access, is essential for breaking the colonial extraction pattern.

Climate Vulnerability and Energy System Resilience

Climate change introduces a compounding risk to Africa's energy system: the same hydropower resources that offer low-carbon electricity are the most vulnerable to the climate variability that is already intensifying across the continent (Carvalho & Santos, 2023). The near-shutdown of Lake Kariba's hydropower station in 2019–2022, when water levels fell to crisis levels due to successive drought years, demonstrated the systemic vulnerability of hydropower-dependent electricity systems. The GERD's filling negotiations are further complicated by climate uncertainty: the inflow projections that underpin the filling schedule are sensitive to climate scenarios that range from modest increase to significant decline in Nile flows.

The emerging agenda for climate-resilient energy planning includes diversification of generation portfolios to reduce hydropower dependency, distributed generation as a resilience strategy that reduces vulnerability to centralized infrastructure failure, and insurance and financial instruments for climate-proofing energy investments. The African Risk Capacity, a specialized agency of the African Union, provides parametric insurance against extreme weather events, but its coverage of energy infrastructure remains limited. Figure 3 illustrates this climate-energy paradox confronting Africa's energy systems. Mainstreaming climate resilience into energy planning requires integrating climate projections into generation expansion models, designing infrastructure to withstand more extreme weather events, and developing contingency plans for climate-induced supply disruptions.

Figure 3: Africa's climate-energy paradox: negligible emissions, disproportionate vulnerability



Comparative Analysis of National Strategies and Regional Power Pools

Regional power pools have demonstrated the technical and economic benefits of electricity trade in Africa, but their impact remains limited by inadequate transmission infrastructure, non-payment disputes, and the tension between national energy sovereignty and regional market integration (Odetayo & Walsh, 2021; Rose & Perez-Arriaga, 2022). The four major African power pools — the Southern African Power Pool (SAPP), East African Power Pool (EAPP), West African Power Pool (WAPP), and Central African Power Pool (CAPP) — represent the institutional framework for regional electricity integration. Their performance, however, varies substantially, reflecting differences in market design, institutional capacity, and the political commitment of member states.

Regional Power Pools: Architecture, Performance, and Constraints

Market design matters more than physical interconnection: the SAPP's competitive day-ahead market has delivered greater trading volumes and price convergence than the EAPP's bilateral-contract model, despite comparable interconnection investment. The SAPP, established in 1995, is the most advanced power pool on the continent, with a competitive short-term energy market, a day-ahead market, and a balancing market. Trading volumes have grown steadily, with South Africa, Mozambique, and Zambia as the largest exporters and Zimbabwe, Botswana, and Namibia as significant importers. The SAPP's success, however, is relative: cross-border electricity trade still accounts for less than 10% of total generation in the region.

The EAPP, by contrast, has focused on bilateral contracts between utilities rather than competitive market mechanisms. The result has been lower trading volumes and limited price convergence, despite significant interconnection investment. The WAPP and CAPP are at earlier stages of development, with limited interconnection infrastructure and minimal trading volumes. The persistent barriers to regional power trade are institutional rather than technical: inadequate transmission links between member states, non-payment by offtakers that undermines trust in commercial arrangements, and the reluctance of larger members particularly South Africa and Egypt to cede dispatch authority to regional institutions. The Africa Continental Free Trade Area (AfCFTA) provides a potential framework for deepening energy integration, but the translation of trade agreements into operational electricity markets requires political commitment that has been inconsistent (Odetayo & Walsh, 2021).

National Strategy Exemplars: South Africa, Kenya, Morocco, and Ethiopia

The contrastive experiences of South Africa (competitive procurement), Kenya (geothermal public investment), Morocco (strategic solar CSP) and Ethiopia (mega-hydropower) reveal that procurement design and risk allocation rather than technology choice or resource endowment — are the primary determinants of energy project success in Africa. South Africa's REIPPPP is the continent's most successful renewable energy procurement program, attracting $14 billion in private investment since 2011 and procuring over 6,000 MW of renewable capacity. The program's success is attributable to its competitive auction design, the provision of government guarantees that mitigate off taker risk, and the transparent, predictable procurement schedule that enabled the development of a domestic renewable energy industry.

Kenya's geothermal development has delivered the highest share of renewable electricity in the region, with geothermal accounting for over 40% of the country's generation. The Kenya Electricity Generating Company (KenGen) and the Geothermal Development Company have pursued a public investment model, with concessional finance from DFIs supporting exploration and drilling. The model has been successful in scaling geothermal capacity, but the capital intensity of geothermal development exploration drilling costs are high and success rates are uncertain limits its replicability in countries without Kenya's institutional capacity and DFI relationships.

Morocco's Noor solar complex, one of the world's largest concentrated solar power (CSP) installations, demonstrates the potential of strategic public investment in solar with storage. The Noor complex, with a total capacity of 580 MW, includes CSP with molten salt storage that enables dispatchable renewable generation. The project was financed through a combination of concessional loans from DFIs, climate finance from the Green Climate Fund, and Moroccan government equity. Ethiopia's GERD illustrates the geopolitical complexities of hydropower development in transboundary basins. The 6,450 MW project, when fully operational, will more than double Ethiopia's installed capacity and position the country as a regional power exporter. However, the filling and operation of the dam have been the subject of intense negotiations with downstream Egypt and Sudan, with the dispute remaining unresolved after more than a decade of talks.

Research Gaps, Evidence-Strength Assessment, and Open Debates

The Africa energy literature exhibits a pronounced evidence hierarchy: micro-level welfare impacts of electrification are well-documented, but meso-level evidence on firm productivity, macro-level evidence on growth multipliers, and political-economy evidence on reform feasibility remain thin or absent, limiting the evidence base for policy design. The evidence on the price elasticity of PAYG solar adoption and the welfare impacts of electrification on households is relatively robust, supported by randomized controlled trials and quasi-experimental studies. However, the evidence on the causal effect of energy access on firm productivity is contested, with studies reaching divergent conclusions depending on context, methodology, and the definition of energy access.

The evidence on the employment multipliers of renewable energy investments in Africa is essentially absent, as is the evidence on long-term grid-defection scenarios and the political economy of utility reform at scale. Table 4 maps the current evidence base across key research domains, identifying the most urgent gaps for future investigation. The major unresolved debates in the literature include: whether natural gas should serve as a transition fuel for African economies or whether the continent should leapfrog directly to renewables; whether off-grid solutions reinforce or reduce energy inequality by creating a two-tier energy system; and whether regional power pools can survive political shocks, such as the suspension of a member state or a major non-payment dispute. These gaps are not merely academic; they limit the evidence base for policy design at a time when African governments are making multi-billion-dollar decisions about energy infrastructure with consequences that will extend for decades.

Table 4: Evidence-strength assessment across research domains

Research domain	Evidence strength	Key gaps	Priority
Household welfare impacts of electrification	Robust	Productive use evidence	Medium
PAYG solar adoption determinants	Robust	Long-term sustainability	Medium
Firm productivity and energy access	Thin	Causal identification	High
Employment multipliers of renewable energy	Absent	National and local estimates	High
Political economy of utility reform	Thin	Reform feasibility conditions	High
Regional power pool performance	Moderate	Distributional effects	Medium

Conclusion and Policy Recommendations

This review has examined Africa's energy matrix through an evaluation framework, synthesizing evidence on the composition, drivers, and sustainability of the continent's energy transition. Five cross-cutting conclusions emerge from the analysis. First, Africa's energy mix is diversifying but the pace of transition is insufficient to meet SDG 7 by 2030. The shift from traditional biomass dominance toward modern renewable diversification is underway, driven by declining technology costs and increasing investment, but the absolute number of people without electricity access has not declined in several sub-Saharan African countries. The persistence of traditional biomass dependence affecting over 600 million people reflects the structural challenge of affordability and supply chain development that clean cooking interventions have yet to resolve.

Second, the financing gap is fundamentally a risk-perception problem requiring de-risking instruments at scale. Africa's cost-of-capital premium 2–3 times higher than developed markets renders economically viable renewable projects uneconomic. Closing this gap requires a combination of guarantee instruments, currency hedging facilities, and blended finance structures that can absorb the political and currency risks that deter private capital. The scale of the required investment an estimated $60–90 billion annually exceeds the capacity of development finance institutions alone and demands the mobilization of private capital at an unprecedented scale.

Third, off-grid solutions have proven their commercial viability but require deliberate integration with grid planning to avoid a two-tier energy system. PAYG solar and mini-grids have transformed the economics of rural electrification, connecting millions of households that grid extension would not have reached for decades. However, the technology ceiling of Tier 1–2 access limits the developmental impact of these solutions, and the risk that off-grid systems become a permanent, lower-quality substitute for grid infrastructure is real. Integrated energy planning that treats off-grid solutions as a bridge to higher-tier access — rather than a permanent solution — is essential.

Fourth, regional power pools are underperforming relative to their potential due to political and institutional, not technical, barriers. The SAPP's relative success demonstrates that competitive market design, transparent trading rules, and credible dispute resolution mechanisms can deliver significant benefits. Extending this model to other power pools requires political commitment to cede dispatch authority to regional institutions, investment in transmission interconnections, and resolution of the non-payment challenges that undermine commercial trust.

Fifth, Africa's climate position — negligible historical emitter, disproportionate climate victim — demands a global framework that separates the right to develop from the right to pollute. The international climate regime must recognize Africa's right to energy-led development and provide the financial and technological support required for a low-carbon development pathway. The current architecture, in which African NDCs are conditional on external finance that has not materialized at the pledged scale, is inadequate to the challenge.

Based on these conclusions, the following policy recommendations are offered, organized by stakeholder. For African governments: prioritize utility reform — including cost-reflective tariffs, independent regulation, and transparent procurement — as the single most impactful policy lever for accelerating energy transition; develop integrated energy plans that coordinate grid extension, mini-grids, and standalone systems to avoid stranded investments and two-tier energy access; and design fuel subsidy reform programs that protect vulnerable households while redirecting fiscal resources to clean energy investment. For development finance institutions: scale up guarantee and de-risking instruments that address the cost-of-capital premium; support the development of standardized project documentation and procurement frameworks that reduce transaction costs for private investors; and increase concessional finance for clean cooking, which remains dramatically underfunded relative to its health and environmental impacts. For private investors: recognize the commercial viability of African renewable energy markets, particularly in countries with credible procurement frameworks; invest in the mini-grid sector, which offers a significant growth opportunity as regulatory frameworks mature; and engage with the clean cooking sector, which represents a large, underserved market with significant social impact potential. For the international climate regime: operationalize the loss and damage fund to address Africa's climate vulnerability; ensure that carbon market mechanisms provide genuine additional finance rather than offsetting developed-country emissions at Africa's expense; and support technology transfer and domestic manufacturing capacity for clean energy technologies, to ensure that Africa captures a greater share of the value chain.

The research agenda for the next generation of energy scholarship on Africa must address the most urgent evidence gaps. Priority areas include: causal evidence on the relationship between energy access and firm productivity, using quasi-experimental methods where randomized trials are infeasible; estimates of the employment multipliers of renewable energy investments across different technologies and country contexts; political-economy analysis of the conditions under which utility reform is politically feasible; and long-term scenario analysis of grid-defection dynamics and their implications for the utility business model. Addressing these gaps will require methodological innovation, sustained research funding, and close collaboration between researchers and policy-makers to ensure that evidence informs the energy decisions that will shape Africa's development trajectory for decades to come.

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