IOP Publishing Environ. Res.: Energy 2 (2025) 013001 https://doi.org/10.1088/2753-3751/ada77d

ENVIRONMENTAL RESEARCH
ENERGY

CrossMark

OPEN ACCESS

RECEIVED
26 September 2024

REVISED
17 December 2024

ACCEPTED FOR PUBLICATION
8 January 2025

PUBLISHED
28 January 2025

PERSPECTIVE

Unearthing the reality of 'Zombie energy systems' in Africa's energy transition

Michael O Dioha[1,*], **Magnus C Abraham-Dukuma**[2] **and Prudence Dato**[1]

[1] Energy and Climate Innovation in Africa Program, Clean Air Task Force, Boston, MA 02109, United States of America
[2] Just Transition Network, Jakarta, Indonesia
[*] Author to whom any correspondence should be addressed.

E-mail: michael@dioha.us and mdioha@catf.us

Keywords: Africa, energy transition, energy efficiency, Zombie energy, energy access

Supplementary material for this article is available online

Abstract

Africa's energy transition is unique and complicated by—among other things—the pervasive presence of 'Zombie Energy Systems' (ZES). These are outdated, inefficient, and environmentally harmful energy systems that persist despite being obsolete (e.g. old and mismanaged electrical grid systems and obsolete electrical appliances). These ZES hinder Africa's energy transition, yet they receive limited attention in the international energy development arena. Rooted in colonial-era legacies, economic constraints, and policy shortcomings, these energy systems have led to a persistent misalignment between energy supply and development goals, perpetuating energy poverty and limiting economic growth. In this piece, we identify ZES as a critical barrier to Africa's energy transition, arguing that addressing it requires more than just infrastructure replacement. A holistic approach is needed—one that includes decommissioning outdated assets, modernizing grids, promoting energy efficiency, improving regulatory environment and fostering local expertise in modern energy systems. We advocate for a comprehensive reevaluation of energy policies and investment strategies across Africa, emphasizing the importance of balancing the development of new energy systems with the critical need to upgrade and enhance existing inefficient energy systems. Neglecting the improvement of current energy systems risks undermining the effectiveness of Africa's energy transition. Furthermore, we highlight the necessity of implementing tailored solutions that address the distinctive energy challenges faced by each country on the continent.

1. The context of Africa's energy transition

The term "energy transition" has, in many instances, been used to describe the shift of the energy industry from reliance on fossil fuels such as oil, natural gas, and coal, to low carbon energy sources like wind and solar power, as well as technologies such as lithium-ion batteries (Huhta and Romppanen 2023, IRENA 2023). In a different fashion, Smil (2017) has defined energy transition as 'the change in the composition (structure) of primary energy supply, the gradual shift from a specific pattern of energy provision to a new state of an energy system.' However, these positions do not fully reflect the complexity of Africa's energy transition.

By 2050, the world population is expected to hit 9.7 billion (United Nations Department of Economic and Social Affairs 2022). Between 2022 and 2050, the population of sub-Saharan Africa (SSA) is projected to nearly double, exceeding 2 billion people by the late 2040s (United Nations Department of Economic and Social Affairs 2022). This forecast suggests that over a quarter of the global population will be African. Rapid urbanization is anticipated, with over half a billion people expected to join Africa's urban population by 2040 (IEA 2022a). These demographic shifts will notably increase energy demand and carbon emissions without any substantial changes in the energy system. Compounding this challenge is the urgent need to provide electricity access to about 600 million people in Africa by 2030 (IEA 2023a). Approximately two-thirds of the global population living in extreme poverty reside in SSA (World Bank 2024). Given these realities and recognizing the critical interplay between energy and the United Nations sustainable development goals

(SDGs), addressing the obstacles and opportunities in providing energy services in Africa is increasingly vital. Additionally, climate change poses a significant threat to the continent. According to the African Development Bank, Africa is experiencing a loss of 5%–15% of its per capita gross domestic product due to climate change and projections are much worse in the future, reaching 16%–64% by 2030 under the high warming scenario (RCP8.5) (AfDB 2022). The foregoing underscores the importance of transitioning to cleaner energy sources and adapting to climate impacts.

Therefore, the energy transition in Africa transcends mere decarbonization; it is also about achieving broader social and economic development objectives, making it a multifaceted and inclusive endeavor. From an African perspective, the energy transition is about uplifting citizens out of poverty while simultaneously navigating an energy transition towards net-zero emissions (Perlaviciute *et al* 2021, Odarno 2023). In essence, Africa finds itself at a crossroads, balancing development aspirations and environmental sustainability (Mutiso 2022, Bignoli *et al* 2024). As the continent strives to pass through this crossroads, it faces a unique challenge known as 'Zombie Energy Systems' (ZES).

While the term 'zombie' typically evokes images of the undead, in the energy domain, here, it refers to outdated, inefficient, and often environmentally damaging energy systems that persist despite being obsolete. We coined the term to describe obsolete or stranded energy assets that continue to linger despite their detrimental impact on progress (Anthony *et al* 2015, Macey 2020, Wu *et al* 2023). These assets are often characterized by their limited efficiency, and high maintenance costs. In Africa, ZES takes various forms in the supply and demand side of the energy system. In the supply side, it includes ageing coal- and natural gas-fired power plants, obsolete hydro-electric dams, diesel/gasoline generators and poorly maintained transmission and distribution (T&D) systems among others. In the demand side, it encompasses inefficient domestic appliances, obsolete boilers, old vehicles and inefficient motors among others (NOPEC 2023).

The global energy transition is primarily focused on shifting from fossil fuels to low and zero carbon energy sources. ZES, often tied to outdated fossil fuel projects, does not align with these goals. As a result, international development efforts, which are increasingly driven by fuel replacement agendas, may overlook refurbishing and investing in new additional capacities of these facilities in favor of projects that contribute directly to decarbonization and the adoption of clean energy (Ramachandran 2021, Moss and Ramachandran 2021). Currently, international development agencies and investors often prioritize new, innovative projects that promise rapid results and visible impacts in Africa. This focus on 'new and shiny' initiatives can overshadow the importance of addressing existing, failing energy infrastructure. The appeal of new renewable energy projects, in particular, solar PV mini grids and solar home systems, which align with global climate goals, often diverts attention from the more complex, less glamorous task of rehabilitating ZES. Restoring or repurposing ZES is often complex and expensive. It requires a detailed assessment of the existing facilities, extensive repairs or upgrades, and often, overcoming bureaucratic and political hurdles. In contrast, developing new projects can be more straightforward and easier to fund, making them more attractive to international donors and investors.

Governments are sometimes reluctant to address these problems due to the potential for political fallout or the perceived high cost of action. Additionally, the sunk costs sometimes associated with ZES can create economic disincentives to acknowledge or address the issue (THE PUNCH 2020). Ignoring ZES in Africa poses significant challenges to the continent's energy transition. The existence of non-functional or underperforming energy systems can drain resources, create inefficiencies, and undermine efforts to expand access to reliable energy. For Africa to achieve a successful energy transition, it is crucial to address these ZES.

Thus, the central question underpinning this piece is: What factors contribute to the persistence of Zombie Energy Systems in Africa, and what actionable solutions can address this challenge in the continent's energy transition? Consequently, we explore the complexities of ZES within Africa's energy transition, exploring its origins, implications, and charting a path forward. We employ a desk-based approach, synthesizing insights from academic literature, international reports, and policy documents. While not a systematic review, we integrate diverse sources to articulate the concept of 'Zombie Energy Systems' and its implications for Africa's energy transition from our point of view. We reviewed documents based on their relevance to Africa's energy transition debates, particularly those highlighting the interplay between historical infrastructure legacies, policy, and socio-economic constraints in Africa.

A key contribution of this perspective is its call for a more comprehensive approach to Africa's energy transition. We critique the current focus of international energy development, which prioritizes new renewable energy projects over addressing ZES. We argue that neglecting ZES perpetuates energy poverty and limits Africa's economic growth, as these obsolete systems consume resources but fail to meet energy demands effectively. We call on policymakers and international development agencies to reconsider their strategies and adopt solutions tailored to Africa's unique needs—balancing both development goals and environmental sustainability. The piece also offers a critical examination of the structural issues behind

Africa's energy system, emphasizing that without addressing ZES, the continent's energy transition will remain incomplete.

2. Some origins of ZES in Africa

The prevalence of ZES in Africa can be traced back to a combination of historical factors, poor maintenance culture, economic constraints, and inadequate policy frameworks. Colonial legacies left many African nations with energy infrastructure geared towards resource extraction rather than domestic development (Taylor 2018). Some colonial powers developed energy infrastructure specifically to support mining operations, such as coal mines in South Africa or mineral extraction in countries like the Democratic Republic of Congo. The energy generated was often used to power machinery and transport systems for extracting and exporting resources back to the colonizing countries. These colonial legacy infrastructures were not designed with the intent of broader electrification/development of these African countries. But some of these countries still rely on the infrastructures for broader electrification without commensurate scale of planning, thus evincing and perpetuating a misalignment of priorities. This misalignment of priorities and the limited maintenance of colonial-era energy infrastructure have contributed to the persistence of ZES in Africa. One such example is the construction of the Kariba Dam on the Zambezi River, which straddles the border between Zambia and Zimbabwe[3] Built in the late 1950s by the British colonial government, the Kariba Dam was intended to supply electricity primarily for the copper mines in Zambia and for urban centers in both countries (Zambia and Zimbabwe), while also serving irrigation purposes for large-scale agriculture. After gaining independence, Zambia and Zimbabwe inherited this hydroelectric project but often struggled to maintain it due to a lack of resources, technical expertise, outdated technology, and political will (GBA 2022). As a result, the dam has deteriorated over time, becoming inefficient/non-functional but still occupying physical space and requiring resources for upkeep. The situation is further worsened by Zambia's recent power crisis, resulting from severe drought conditions affecting the Kariba hydropower plant that leads to economic losses due to nationwide blackouts (Harlan 2024).

In addition to colonial legacy issues, today, many energy projects in Africa suffer from inadequate planning and execution. A typical example of a ZES in Africa resulting from inadequate planning and execution is Nigeria's electricity generation and transmission system. Despite having an installed electricity generation capacity of approximately 16 GW, the transmission system in Nigeria can only effectively transmit around 7.5 GW of power (Babatunde *et al* 2023). This disparity between generation capacity and transmission capacity reflects a failure in planning and execution, leading to an inefficient use of resources and infrastructure. As a result, many electricity generation projects in Nigeria operate below their intended capacity, contributing to chronic power shortages and blackouts across the country (Tambari *et al* 2020). These underutilized or inefficiently utilized power generation assets represent a form of ZES, as they do not effectively contribute to meeting the energy needs of the population despite significant investments in their development. Moreover, the weak transmission system further limits the grid integration of renewable energy sources which require well-functioning grid.

Even when energy projects are successfully implemented, the lack of maintenance and sustainability measures turn them into zombie projects, leading to decreased efficiency and reliability. Many power T&D networks in Africa were built several decades ago and have not undergone major rehabilitation or modernization efforts. Moreover, some were built with old and outdated inputs to minimize cost. This ageing infrastructure is prone to breakdowns, inefficiencies, and reliability issues, contributing to frequent power outages and service disruptions.

Figure 1 shows the T&D losses across countries in Africa compared to international standard. Only Botswana, Lesotho, and Mauritius have T&D losses of 10% or less. In the other 36 countries, T&D losses ranged from 11% in Swaziland to about 48% in Central African Republic. African countries' T&D systems suffer from some of the highest energy losses globally. These T&D losses constitute a substantial financial burden for numerous utilities across Africa. Non-technical losses, particularly the non-payment of utility bills by state agencies and municipalities, significantly contribute to the persistence of ZES in Africa. These losses result in massive and unsustainable utility debts, which hinder the financial viability of energy providers and limit their capacity to invest in infrastructure upgrades or modern technologies. For instance, in South Africa, Eskom's financial struggles are partly attributed to unpaid municipal debts, which amounted to about $4.5 billion USD as of 2024 (Bloomberg 2024).

[3] Details of Kariba dam failure available at: www.nytimes.com/interactive/2020/07/22/magazine/zambia-kariba-dam.html.

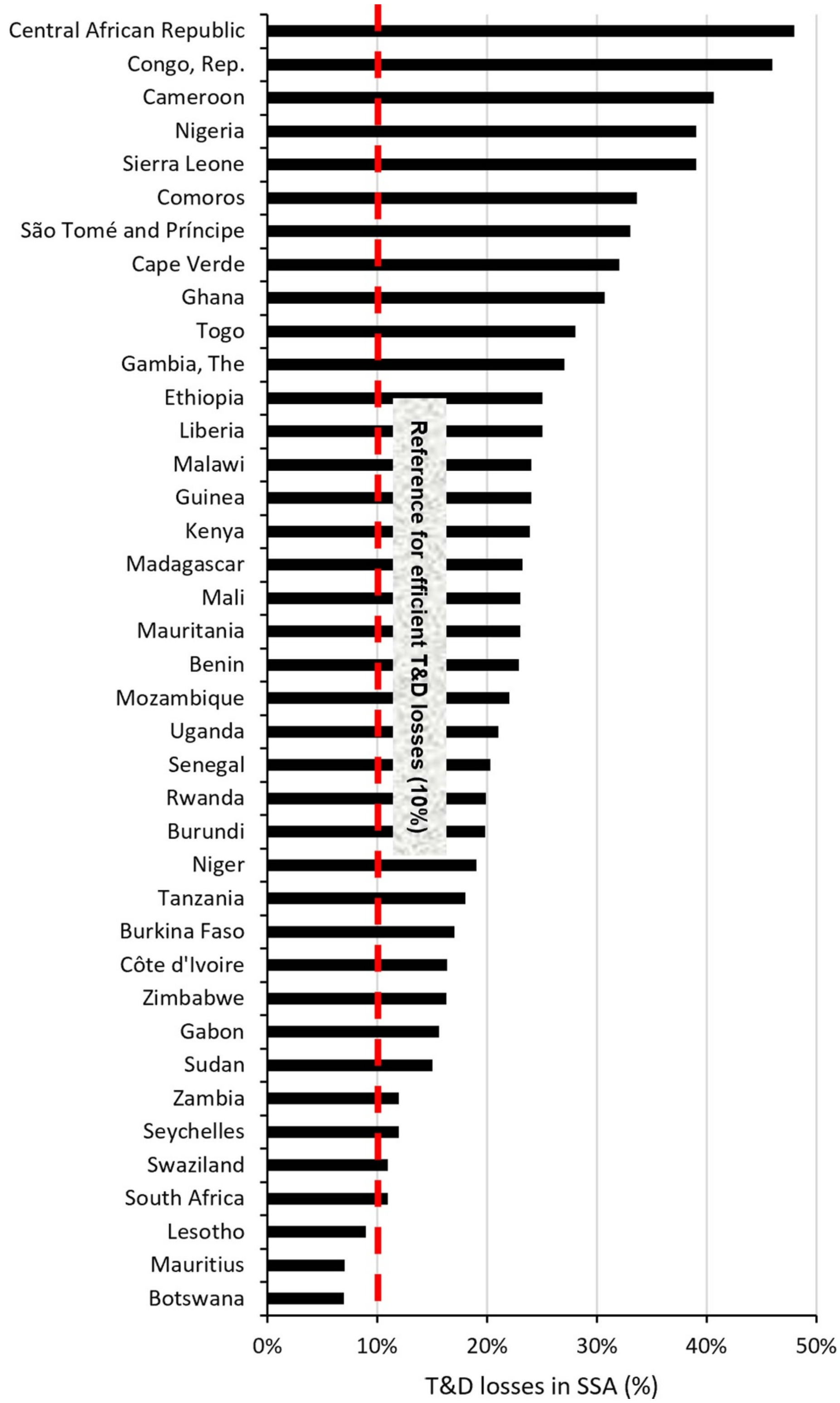

Figure 1. Transmission and distribution (T&D) losses. The international T&D standard for efficient power systems is taken as 10% and below. (Data *Source*: Authors' compilation - see supplementary file).

3. Manifestations of ZES in Africa

ZES manifests in various forms across the entire spectrum of the energy systems of African countries. On the supply side, between January 2010 and June 2022, Nigeria experienced 222 instances of partial or complete grid collapses, attributed to factors such as demand surpassing supply, outdated infrastructure, and insufficient transmission lines (Oladapo 2023, Baskaran and Coste 2024). Similarly, South Africa grapples with grid instability, notably through 'load shedding,' which has escalated since 2007. Load shedding

Table 1. Used vehicles import age limits of African countries.

3 yrs and below	4 and 5 yrs	6–8 yrs	9 yrs +	No age limits
Algeria, Mauritius	Chad, Cote D'Ivoire, Gabon, Lesotho, Mauritania, Morocco, Tunisia	Angola, Djibouti, Kenya, Namibia, Senegal	Burundi, Democratic Republic of Congo, Libya Nigeria, Uganda	Benin, Botswana, Burkina Faso, Cameroon, Cape Verde, Central African Republic, Comoros, Congo, Equatorial Guinea, Eritrea, Eswatini, Ethiopia, Gambia, Guinea, Guinea-Bissau, Liberia, Madagascar, Malawi, Mali, Mozambique, Niger, Rwanda, Sao Tome and Principe, Sierra Leone, Somalia, South Sudan, Tanzania, Togo, Zambia, Zimbabwe

incidents lasting from 2 to 12 hours daily occurred for 332 days between January 1 and 11 December 2023, (Baskaran and Coste 2024). Approximately 85% of South Africa's coal-powered electricity is produced by ageing and poorly maintained power stations. Eskom, the state-owned utility responsible for 95% of South Africa's electricity generation, has seen a decline in its energy availability factor from 75% in 2014– 58% in 2023 (Baskaran and Coste 2024).

On the demand front, Africa has also become a destination for cheap, second-hand, and outdated appliances, primarily sourced from households in Europe and sometimes illicitly resold in Africa (Gyamfi *et al* 2018). The demand for these appliances in Africa stems from the limited incomes of African households, constraining their ability to afford new and efficient appliances. For instance, between 2004 and 2014, Ghana imported over 3.7 million refrigerators, with approximately 75% of them being second-hand (Gyamfi *et al* 2018). Similarly, a United Nations-backed analysis of 60 000 metric tons of used electrical equipment imported into Nigeria annually, predominantly from Europe, revealed that at least a quarter of it was non-functional, including a significant portion of refrigerators and air conditioners (Odeyingbo *et al* 2018). These second-hand cooling devices often consume about two to three times more electricity than new models, thereby placing additional strain on already stretched electricity grids (Fleming 2020). Consequently, low-income households in Africa bear the burden of high electricity bills, further exacerbating the cycle of poverty. Moreover, the prevalence of these inefficient appliances hampers efforts to reduce emissions and slows down Africa's energy transition.

While a large part of this piece has given considerable attention to expounding ZES phenomenon from the electricity systems perspective, it is worth noting that this phenomenon can be observed in other aspects of the energy sector such as transportation, industry, and agricultural energy systems. From this exposition, we would briefly shed some lights on the transportation sector. It is imperative to quickly note that our focus on the transportation sector do not by implication represent an exhaustive identification of the concept of ZES that needs discussion. Given our limited number of words, the transportation sector arguably serves as a reference point for drawing valuable insights on ZES phenomenon beyond the electricity system.

Today, many African countries rely heavily on second-hand or outdated vehicles imported from other regions, particularly Europe, Asia and North America (Ayetor *et al* 2021). Approximately 85% of the automotive fleet in Africa consists of second-hand vehicles. Nigeria leads the continent in this regard, recording imports of 171 248 used light-duty vehicles in 2019 (Gicha *et al* 2024). Most of these vehicles imported into Africa are over a decade old and often lack modern fuel efficiency technologies and emit higher levels of greenhouse gases and air pollutants. For example, in Uganda and Nigeria, the average age of vehicles on the road is 16 years (approximately 5 years older than vehicles in Europe and U.S.) (Cash 2022, UNEP 2023), contributing to increased fuel consumption and exacerbating urban air pollution. Table 1 shows the age limits of imported vehicles in Africa adapted from a study by the United Nations Environment Programme (UNEP 2020). From table 1, it may be observed that about 30 countries (over 50% of the total number of countries in Africa) do not have any age limit on imported vehicles.

Moreover, the railway systems in many African countries remain underutilized due to outdated infrastructure and limited rail network, forcing a greater reliance on road transport for freight (Bouraima *et al* 2023). This is energy-intensive and results in relatively higher emissions. Zambia's railway system, designed during the colonial era, struggles to compete with road transport, despite being a more energy-efficient option for moving goods (Sikazwe *et al* 2020). Additionally, the global transition to electric and alternative-fuel vehicles is slow in Africa due to high costs, lack of charging infrastructure, and limited policy incentives (Dioha *et al* 2022). This delay perpetuates reliance on fossil-fuel-powered vehicles. South Africa, despite being a SSA regional leader, has a limited number of electric vehicles (EVs) per capita compared to countries like China and Norway (Tongwane and Moeletsi 2021, IEA 2022b). A recent study of the Global Fuel Economy Initiative for the Economic Community of West African States (ECOWAS) shows that the average fuel economy in countries with available baseline studies varies significantly, with Ghana reporting 6.99 liters of gasoline equivalent per 100 kilometers (lge/100 km) in 2016, while Nigeria recorded 9.19 lge/100 km in 2017. Both figures exceed the proposed ECOWAS average fuel economy of 5 lge/100 km (GFEI 2020).

Earlier, we construed Africa's energy transition as the need for socio-economic development while simultaneously reducing emissions. However, the persistence of ZES remains a problem for this Africa's dual objective. From the socio-economic side, as demonstrated in the preceding paragraphs, ZES represents a drain on government, households and businesses resources. For instance, for utilities, ZES leads to significant technical losses as outdated infrastructure requires significant maintenance and repair costs, diverting funds that could be invested in modernizing their energy infrastructure; making it ready to integrate renewable and other clean energy systems. ZES could also divert national investment away from renewable energy projects, hindering the continent's ability to harness its abundant natural resources for sustainable development. Moreover, reliance on fossil fuel-powered generators and inefficient T&D system perpetuates energy poverty, as high electricity prices and unreliable supply systems limit electricity access for millions of people, particularly in rural areas. From an environmental perspective, ZES contributes to air pollution, as well as greenhouse gas emissions, exacerbating the impacts of climate change and undermining efforts to achieve carbon neutrality in Africa. Continued reliance on ZES can impede the adoption of newer, cleaner technologies, trapping African countries in outdated energy systems and hindering innovation.

4. The persistence of ZES in Africa

Earlier in this piece, reference has been made to colonial legacy energy infrastructure as being at the heart of some ZES in Africa, especially from a central power generation and transmission perspective. The persistence of ZES across African countries is a manifest reflection of a multitude of challenges, ranging from political corruption and economic barriers to technological and institutional constraints. Here, several elements can be brought to sharp focus as illustrative and not exhaustive representations of the barriers and constraints. Political corruption looms large (Imam *et al* 2019). Over the years, successive governments in several African countries have allocated significant funds to finance energy infrastructure projects. In some cases, these projects have not materialized to support the much-needed improvements to electricity generation and transmission. There are striking examples. In Nigeria, between 1999 and 2007, the government committed $16 billion to electricity infrastructure through a purported National Integrated Power Project (NIPP) with no results (SERAP 2017). Investigation by the Nigerian state is yet to yield any fruit in terms of criminal responsibility and punitive action, thus festering a culture of corruption, impunity, and lack of accountability. This is just one example. In South Africa, it has been reported that institutional corruption is directly responsible for the state-owned utility's (Eskom's) inability to generate and transmit sufficient electricity, and costs Eskom an average of $55 million monthly (Rédaction Africanews 2023).

The dysfunctional energy infrastructure in most African countries resulting in epileptic electricity access has occasioned a surge in private power generation through the large-scale deployment of mobile electric power generators (EPGs) by small and medium enterprises (SMEs) and households. Research by the World Bank's International Finance Corporation estimates that about 6.5 million generators are deployed in SSA, with about 3 million in Nigeria alone (World Bank 2019). In Nigeria, over 80% of SMEs rely on EPGs for their business operations (Roy *et al* 2023). We opine that this high reliance on EPGs to power businesses and household appliances births the notion that most private citizens in Nigeria and some other SSA countries are 'Independent Power Ministers' as they independently provide electricity services for themselves. This circumstance has created a lucrative market for the sale of EPGs, to the extent of the alleged presence of a strong mafia protecting the financial interests of profiteers of this trade. The theory underpinning the festering of ZES, whether apocryphal or spurious—as far as the use of EPGs goes—is that political cronies have vested financial interests in the EPGs market, thus coalesce to frustrate plans to revamp ailing and ageing electricity infrastructure or ensuring constant electricity access due to the potential loss of business and profits associated with the EPGs market (Garside 2012). There has been no widely known effort by the Nigerian state to actively investigate the existence, prevalence, and activities of the EPGs mafia to fester the persistence of ZES and epileptic electricity supply for their business interests. This is an issue that deserves scrutiny to demystify the extent to which the EPGs market promotes a culture of inefficiency (sometimes exacerbated by the electric utilities) and the prevalence of ZES in Nigeria and other SSA countries.

The economic constraints that enable prevalence of ZES in Africa are evident at the central energy system level and at the local energy system level. There could be specific examples, but we will only provide a broadbrush discussion to illustrate the magnitude of the challenge facing African countries. At the national level, African economies are grappling with the macroeconomic factors of output, high interest rates, production, expenditure, income, and gross domestic product, with some governments in debt to international financial institutions and creditor countries. In addition to the preponderance of this economic malady, SSA countries are having to confront the huge costs of energy and electricity projects more broadly. As far back as 2012, researchers assessed the investment cost for providing electricity to SSA over a 10 year period to range from 160 and 215 billion United States dollars (US$) (Rosnes and Vennemo 2012). To put the investment needs in a more contemporary perspective, the International Energy Agency (IEA) estimates the cost of bringing access to modern energy for all Africans calls for investment of US$25 billionper year to 2030 (IEA 2022a). This huge cost requirement presents a financial challenge to the ability of many SSA countries to transition away from ZES to modernized and efficient energy infrastructure to achieve the goal of SDG7: affordable, reliable, sustainable, and modern energy for all by 2030. Moreover, other factors such as the substantial costs tied to the petroleum industry and socio-political dynamics such as the presence of cartels and the provision of subsidies, can significantly impede progress towards modern and cleaner energy sources like in oil-rich Nigeria. These elements have the potential to delay, obstruct, or even reverse decisions that prioritize the adoption of renewable energy sources (Pavanelli *et al* 2023).

At the micro local household level, the diffusion of energy-efficient appliances and technologies is a function of multifaceted factors ranging from intuitive behavioral tendencies and the socio-economic characteristics of different demographics and households (Ali *et al* 2021, Hassen *et al* 2023, Baidoo *et al* 2024). Behavioral tendencies such as attitude, subjective norm, past purchase experience, and level of receptibility to information can influence people's decision to purchase energy-efficient appliances, and by so doing stamp out ZES at the household level. However, the socio-economic status or circumstances of households can also influence how much consumers are willing to spend to purchase appliances. A family struggling to buy food and pay rent from meagre income will prioritize groceries over appliances with high energy-efficiency ratings. This resonates with a fundamental element of the thesis of this piece, i.e. that Africa's energy transition entails achieving broader socio-economic development while pursuing decarbonization goals. Thus, policy focus to address ZES in Africa needs to address these multifaceted characters and elements of the problem. The socio-economic dimension also drives the persistence of ZES in Africa's transportation sector and is further perpetuated by weak policy frameworks; for example, as of 2024, just 28% of African countries have established at least one national target for EVs (Johansson *et al* 2024). Furthermore, the cost barrier is stark: the average price of an entry-level four-wheeler EV model in Africa exceeds US$25 000 (Tyre World 2024), which far exceeds the continent's per capita GDP of US$2955 (Voronoi 2024). This economic disparity drives the demand for cheaper, outdated vehicles. In tandem, the pervasive subsidies on fossil fuels in the region incentivizes the continued use of gasoline and diesel-powered vehicles, stalling cleaner energy transitions.

5. Policy implications and actionable solutions

Can ZES be eradicated in Africa? This question lacks a simple answer. Various African nations grapple with diverse forms of ZES, ranging from outdated power plants and transmission networks to inefficient appliances and vehicles. Although eliminating all forms of ZES may prove elusive, significant headway can be achieved through strategic measures.

At the heart of addressing ZES in Africa is the need for each African country to conduct comprehensive assessments of existing energy systems across its economy to identify zombie assets. This will entail evaluating the age, efficiency, and emissions profile of each plant/system/technology/appliance/process to prioritize decommissioning efforts. Such assessment will identify the technical condition, economic viability, and environmental impact of the existing systems. The comprehensive assessment needs to also identify and prioritize systems that need upgrades and rehabilitation or underutilized infrastructure to enhance efficiency and reliability.

Once this assessment is completed, the next crucial step is to either decommission or upgrade the systems as needed. This action must be undertaken with careful consideration of the potential impact on energy security, grid stability, and local communities, particularly in the African context. For example, in Nigeria—the country with the largest electricity access deficit worldwide (Dioha and Kumar 2020a)—the decommissioning of outdated power plants could initially lead to challenges in meeting electricity demand. However, strategic planning and investment in new generation capacity and renewable energy sources as well as modern grid infrastructure can mitigate these risks while promoting long-term sustainability. Similarly, in South Africa, where coal-fired power plants have long been a cornerstone of the energy system, decommissioning such plants poses challenges for both energy security and local economies dependent on the coal industry. Initiatives such as the just energy transition partnership (JETP) is working to address the economic consequences of job loss in South Africa's energy transition[4]. Any energy or electricity system decommissioning operation in the country should be carried out without undermining the 'justice' dimensions, as this might further exacerbate socio-economic inequities.

The kinds of projects that need decommissioning or rehabilitation will vary from one African country to the other depending on what projects were identified during the assessment process. Examples of project initiatives that could help to address ZES in Africa will encompass refurbishment of the existing grids, continuous investment in renewable and decentralized energy systems as well as introduction of energy efficient appliances and industrial processes. Modernizing the electricity T&D grids to improve reliability, reduce losses, and accommodate variable renewable energy sources will be a key project across many African nations. For example, upgrade of transmission infrastructure like the regional power interconnectors, which aims to improve cross-border electricity trade and grid stability. Additionally, by ramping up investments in renewable energy sources like solar, wind (Oyewo *et al* 2023), and hydroelectric power, coupled with distributed generation technologies such as microgrids (where economically viable), Africa can effectively combat ZES. These innovative approaches enable decentralized energy production, reducing reliance on centralized grids prone to inefficiencies and outages.

Effective power sector regulation and utility management are foundational to addressing the challenges posed by ZES in Africa. A key driver of the persistent inefficiencies in the energy sector is the lack of robust regulatory oversight, which has resulted in systemic issues such as governance failures, underperforming utilities, and the prevalence of non-technical losses. To overcome these challenges, African governments must prioritize the establishment and strengthening of independent regulatory bodies capable of ensuring transparency, accountability, and adherence to performance benchmarks and introduction of smart grids within the energy sector (Dato *et al* 2020, Twesigye 2022, IEA 2023b). Strong regulatory frameworks can drive better utility management by enforcing operational efficiency, incentivizing grid modernization, and enabling the integration of renewable energy sources. For instance, regulators can mandate the adoption of advanced metering infrastructure to reduce non-technical losses, such as electricity theft and non-payment by government agencies. By ensuring timely payment of electricity bills by public institutions, utilities can alleviate financial burdens and redirect resources towards grid upgrades and cleaner energy investments. Furthermore, African governments must also establish mechanisms for monitoring and evaluating utility performance, linking financial support or incentives to measurable outcomes such as reduced technical and non-technical losses.

Building local expertise in modern energy technologies and energy management is crucial for Africa's transition away from ZES. By investing in training programs and capacity building initiatives, African countries can develop a skilled workforce capable of designing, implementing, and maintaining modern energy infrastructure. This not only addresses the skills gap but also empowers local communities and reduces dependency on foreign expertise. One example of such capacity-building efforts is the renewable energy training program in Kenya. This program aims to equip technicians and engineers with the necessary skills to work in the renewable energy sector. Participants undergo comprehensive training in various aspects of renewable energy technologies, including solar, wind, hydro, and geothermal power. International efforts such as the IEA's training of Africans on energy efficiency can also play significant role in equipping Africa's workforce[5].

Implementing energy efficiency measures across various sectors is also crucial for reducing energy waste and improving the productivity of existing infrastructure, thereby mitigating the negative effects of ZES. By promoting energy-efficient appliances, implementing stringent building codes, and optimizing industrial processes, African nations can significantly reduce their energy consumption and reliance on inefficient systems. Encouraging the use of energy-efficient appliances can lead to substantial fossil energy savings if the country's energy source is predominantly from fossil sources. For example, programs that provide incentives or subsidies for the purchase of energy-efficient refrigerators, air conditioners, and lighting fixtures can incentivize consumers to adopt more efficient technologies. In South Africa, the energy efficiency standard and labeling program mandates energy efficiency labeling for various appliances, helping consumers make informed choices and reducing energy consumption. In Nigeria, initiatives like the Nigerian energy support

[4] https://www.iisd.org/articles/insight/just-energy-transition-partnerships.

[5] https://www.iea.org/events/africa-energy-efficiency-policy-in-emerging-economies-training-week.

program provide technical assistance to industries to improve energy efficiency through measures such as energy audits, capacity building, and technology transfer[6].

In terms of progress on the energy efficiency front, efforts to enhance energy efficiency in Africa, led by the African energy efficiency strategy (AEES) under the African energy commission (AFREC) in collaboration with diverse stakeholders, exemplify the potential for significant CO_2 emissions reductions. The strategy aims to establish a sustainable, efficient, and inclusive energy system that promotes environmental sustainability, economic growth, and universal energy access (AFREC 2024). A cornerstone of this strategy is the ambitious target to increase energy productivity by 50% by 2050, underscoring its commitment to mitigating CO_2 emissions across the continent. In addition to the AEES, individual African nations have initiated impactful energy efficiency programs tailored to their unique energy challenges. For example, Ghana's appliance labeling initiative, coupled with regulatory measures, has led to estimated energy savings exceeding 120 MW. These savings have circumvented the need for US$105 million in additional generation infrastructure investments and reduced annual CO_2 emissions by over 110 000 tons (USAID 2024). Similarly, South Africa's energy efficiency incentive schemes, championed by Eskom, have achieved cumulative energy savings surpassing 3 GW over a decade. This achievement is equivalent to the output of five 600 MW generators and has substantially contributed to CO_2 emissions reductions (USAID 2024). These initiatives illustrate how targeted energy efficiency measures can mitigate the effect of ZES and thus drive substantial environmental and economic benefits while advancing Africa's transition to a low-carbon future.

To address the persistence of ZES in Africa's transportation sector, several interventions, supported by successful examples from within the continent, can serve as a blueprint for progress. African governments should implement and enforce stringent vehicle emission standards while incentivizing the adoption of fuel-efficient vehicles and EVs (Dioha and Kumar 2020b, Dioha and Caldeira 2022). For instance, South Africa has introduced fiscal policies, such as reduced import tariffs, to promote EV adoption, a strategy that other African nations can emulate (Tongwane and Moeletsi 2021). Simultaneously, phasing out high-sulfur fuels and promoting cleaner alternatives is crucial; Kenya provides an example, having successfully transitioned to low-sulfur diesel fuels in compliance with international standards, which has significantly improved air quality. Investment in infrastructure remains vital, particularly in developing charging networks for EVs and expanding public transport systems. Ethiopia's electrified light rail system in Addis Ababa (Debebe and Asteray 2022), demonstrates how strategic investments in urban public transport can offer sustainable alternatives to fossil-fuel-based transportation. Encouraging a modal shift from road to rail and water-based freight systems would further enhance energy efficiency and reduce emissions (Dioha and Kumar 2020b).

While implementing these measures could mitigate the adverse impacts of ZES in Africa's energy transition, their effective implementation relies on securing adequate investment in Africa's energy sector. Even though Africa comprises about 20% of the world's population, it presently garners a mere 3% share of global energy investment (IEA 2023c). Therefore, addressing ZES in Africa requires careful consideration of how to mobilize the necessary resources for decommissioning, modernization, subsidizing (efficient appliances & EVs) and replacement of infrastructure, as well as the required manpower development. International organizations (e.g. UNEP), development banks, and private investors play pivotal roles in financing projects aimed at promoting renewable energy development, grid modernization, and energy efficiency improvements in Africa. Innovative financing mechanisms, such as green bonds, impact investment funds, concessional financing, and public-private partnerships, provide new avenues for mobilizing capital toward modern energy and energy efficiency projects on the continent. Tunisia's PROSOL thermal water heater program, a successful demand-side management initiative, offers valuable lessons for reducing dependence on outdated systems through innovative financing. The residential PROSOL financial mechanism aims to overcome two key challenges for end-users: the significant initial capital requirement and the comparatively long payback period associated with traditional technologies (Baccouche 2014).

The recommendations provided above are not exhaustive, and there is no one-size-fits-all approach suitable for the entire African continent. While these suggestions can be broadly adapted, each African country must chart its own pathway in addressing ZES, grounded in local realities. As Africa navigates its energy transition, the specter of ZES looms large, posing a threat to progress towards a sustainable future. However, by gradually phasing out ZES and their associated infrastructure, Africa can unlock its vast energy potential and drive the continent's development in a manner that is inclusive, equitable, and environmentally responsible. Unearthing the reality of ZES presents not just a challenge but an opportunity to shape a brighter, more prosperous future for Africa and the world.

[6] https://www.giz.de/en/downloads/NESP%20II_Factsheet.pdf.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

Acknowledgment

We extend our sincere gratitude to Lily Odarno, Lee Beck, Natalie Volk, and Troy Shaheen of Clean Air Task Force (CATF) for their thoughtful contributions to this piece.

ORCID iDs

Michael O Dioha https://orcid.org/0000-0001-6983-6752
Prudence Dato https://orcid.org/0000-0003-3367-6245

References

AfDB 2022 *African Economic Outlook 2022* (African Development Bank)
AFREC 2024 Energy efficiency programme | AFREC (available at: https://au-afrec.org/energy-efficiency-programme) (Accessed 19 November 2024)
Ali M R, Shafiq M and Andejany M 2021 Determinants of consumers' intentions towards the purchase of energy efficient appliances in Pakistan: an extended model of the theory of planned behavior *Sustainability* **13** 565
Anthony S D, Duncan D S and Siren P M A 2015 Zombie projects: how to find them and kill them *Harv Bus Rev.* (available at: https://hbr.org/2015/03/zombie-projects-how-to-find-them-and-kill-them) (Accessed 21 August 2024)
Ayetor G K, Mbonigaba I, Sackey M N and Andoh P Y 2021 Vehicle regulations in Africa: impact on used vehicle import and new vehicle sales *Transp. Res. Interdiscip. Perspect.* **10** 100384
Babatunde O, Buraimoh E, Tinuoye O, Ayegbusi C, Davidson I and Ighravwe D E 2023 Electricity sector assessment in Nigeria: the post-liberation era *Cogent Eng.* **10** 2157536
Baccouche A 2014 The Tunisian solar thermal market: a change of scale *Energy Proc.* **48** 1627–34
Baidoo A N A, Danquah J A, Nunoo E K, Mariwah S, Boampong G N, Twum E, Amankwah E and Nyametso J K 2024 Households' energy conservation and efficiency awareness practices in the cape coast metropolis of Ghana *Discover Sustain.* **5** 1–18
Baskaran G and Coste S 2024 Achieving universal energy access in Africa amid global decarbonization (available at: https://csis-website-prod.s3.amazonaws.com/s3fs-public/2024-01/240131_Baskaran_Energy_Africa.pdf?VersionId=5H6XEl6W.3YisdwUoqotAo7aFeXIHLU3) (Accessed 30 March 2024)
Bignoli D J *et al* 2024 Towards more sustainable and inclusive development corridors in Africa *Environ. Res.* **4** 035012
Bloomberg 2024 South Africa's delinquent municipalities Owe Eskom $4.5 billion—Bloomberg (available at: www.bloomberg.com/news/articles/2024-08-06/south-africa-s-delinquent-municipalities-owe-eskom-4-5-billion) (Accessed 19 November 2024)
Bouraima M B, Alimo P K, Agyeman S, Sumo P D, Lartey-Young G, Ehebrecht D and Qiu Y 2023 Africa's railway renaissance and sustainability: current knowledge, challenges, and prospects *J. Transp. Geogr.* **106** 103487
Cash K, 2022. Everything you need to know about African EV manufacturing—energy for growth hub (available at: https://energyforgrowth.org/article/everything-you-need-to-know-about-african-ev-manufacturing/) (Accessed 19 November 2024)
Dato P, Durmaz T and Pommeret A 2020 Smart grids and renewable electricity generation by households *Energy Econ.* **86** 104511
Debebe G and Asteray B 2022 Assessment on the current and future performance of Addis Ababa light rail transit service using mathematical modeling *Adv. Civ. Eng.* **2022** 5097929
Dioha M O and Caldeira K 2022 Accelerating electric mobility in Nigeria (Energy For Growth Hub) (available at: www.energyforgrowth.org/memo/accelerating-electric-mobility-in-nigeria/) (Accessed 18 March 2022)
Dioha M O, Duan L, Ruggles T H, Bellocchi S and Caldeira K 2022 Exploring the role of electric vehicles in Africa's energy transition: a Nigerian case study *iScience* **25** 103926
Dioha M O and Kumar A 2020a Exploring sustainable energy transitions in sub-Saharan Africa residential sector: the case of Nigeria *Renew. Sustain. Energy Rev.* **117** 109510
Dioha M O and Kumar A 2020b Sustainable energy pathways for land transport in Nigeria *Util. Policy* **64** 101034
Fleming P 2020 The big chill: how Africa is moving to battle 'zombie' appliances (Thomson Reuters Foundation) (available at: https://news.trust.org/item/20200624102543-fbvis/) (Accessed 17 September 2024)
Garside B 2012 Privatising Nigeria's power sector (International Institute for Environment and Development) (available at: www.iied.org/privatising-nigerias-power-sector) (Accessed 2 June 2024)
GBA 2022 Zimbabwe's energy supply hits rock bottom as Kariba dam and Foreign currency dry up—green building Africa (available at: www.greenbuildingafrica.co.za/zimbabwes-energy-supply-hits-rock-bottom-as-kariba-dam-and-foreign-currency-dry-up/) (Accessed 15 December 2024)
GFEI 2020 West Africa adopts the first ever Africa regional fuel economy roadmap (available at: www.globalfueleconomy.org/news/2020/february/west-africa-adopts-the-first-ever-africa-regional-fuel-economy-roadmap) (Accessed 11 19 2024)
Gicha B B, Tufa L T and Lee J 2024 The electric vehicle revolution in Sub-Saharan Africa: trends, challenges, and opportunities *Energy Strategy Rev.* **53** 101384
Gyamfi S, Amankwah Diawuo F, Nyarko Kumi E, Sika F and Modjinou M 2018 The energy efficiency situation in Ghana *Renew. Sustain. Energy Rev.* **82** 1415–23
Harlan C 2024 Drought is threatening hydropower energy in Zambia, developing nations—the Washington post (available at: www.washingtonpost.com/climate-environment/2024/11/17/zambia-drought-hydropower-climate-change/) (Accessed 19 November 2024)
Hassen S, Anandarajah G and Seifemichael R 2023 Behavioral and socio-economic determinants of urban households' investment in energy efficient technologies: evidence from Ethiopia *Front. Energy Res.* **11** 1135291
Huhta K and Romppanen S 2023 Why is energy law resistant to changes required by climate policies? *Energy Clim. Change* **4** 100096

IEA 2022a Africa energy outlook 2022 (IEA) License: CC BY 4.0 (available at: www.iea.org/reports/africa-energy-outlook-2022)
IEA 2022b Global EV outlook 2022 (IEA) (available at: www.iea.org/reports/global-ev-outlook-2022)
IEA 2023a Access to clean cooking—SDG7: data and projections
IEA 2023b Unlocking smart grid opportunities in emerging markets and developing economies (IEA) Licence: CC BY 4.0 (available at: www.iea.org/reports/unlocking-smart-grid-opportunities-in-emerging-markets-and-developing-economies)
IEA 2023c Financing clean energy in Africa (IEA) Licence: CC BY 4.0 (available at: www.iea.org/reports/financing-clean-energy-in-africa)
Imam M I, Jamasb T and Llorca M 2019 Sector reforms and institutional corruption: evidence from electricity industry in Sub-Saharan Africa *Energy Policy* **129** 532–45
IRENA 2023 World energy transitions outlook 2023: 1.5 °C pathway
Johansson D, Tariq H and Mutiso R 2024 Who in Africa is ready for EVs? (available at: https://energyforgrowth.org/article/who-in-africa-is-ready-for-evs/) (Accessed 21 November 2024)
Macey J 2020 Zombie energy laws *Vanderbilt Law Rev.* **73** 1077
Moss T and Ramachandran V, 2021. Why the climate panic about Africa is wrong—energy for growth (available at: www.energyforgrowth.org/op-ed/why-the-climate-panic-about-africa-is-wrong/) (Accessed 20 November 2022).
Mutiso R M 2022 Net-zero plans exclude Africa *Nature* **611** 10
NOPEC 2023 Zombie appliances: are your devices the living dead? | NOPEC (available at: www.nopec.org/blognewsroom/blog/zombie-appliances) (Accessed 21 August 2024)
Odarno L 2023 COP28 and Africa: getting real about climate action and its barriers in Africa—clean air task force (available at: www.catf.us/2023/11/cop28-africa-getting-real-about-climate-action-barriers-africa/) (Accessed 29 March 2024)
Odeyingbo O, Nnorom I and Deubzer O 2018 Assessing import of used electrical and electronic equipment into Nigeria (available at: https://collections.unu.edu/eserv/UNU:6349/PiP_Report.pdf) (Accessed 30 March 2024)
Oladapo O 2023 Nigeria's national power grid—climate scorecard (available at: www.climatescorecard.org/2023/01/nigerias-national-power-grid/) (Accessed 30 March 2024)
Oyewo A S, Sterl S, Khalili S and Breyer C 2023 Highly renewable energy systems in Africa: rationale, research, and recommendations *Joule* **7** 1437–70
Pavanelli J M M, Sang E V, de Oliveira C E, Dos Reis Campos F, Lazaro L L B, Edomah N and Igari A T 2023 An institutional framework for energy transitions: lessons from the Nigerian electricity industry history *Energy Res. Soc. Sci.* **97** 102994
Perlaviciute G, Steg L and Sovacool B K 2021 A perspective on the human dimensions of a transition to net-zero energy systems *Energy Clim. Change* **2** 100042
Ramachandran V 2021 Blanket bans on fossil-fuel funds will entrench poverty *Nature* **592** 489
Rédaction Africanews 2023 South Africa: corruption costs Eskom $55m a month (Africanews) (available at: www.africanews.com/2023/04/26/south-africa-corruption-costs-eskom-55m-a-month/) (Accessed 2 June 2024)
Rosnes O and Vennemo H 2012 The cost of providing electricity to Africa *Energy Econ.* **34** 1318–28
Roy P, Watkins M, Kelechi Iwuamadi C and Ibrahim J 2023 Breaking the cycle of corruption in Nigeria's electricity sector: off-grid solutions for local enterprises *Energy Res. Soc. Sci.* **101** 103130
SERAP 2017 *From Darkness To Darkness: How Nigerians are Paying the Price for Corruption in the Electricity Sector*
Sikazwe C, Mwanaumo E M, Mambwe M and Mwale R K, 2020. A situational analysis of transport usage in Zambia: a modal perspective of railway freight services from 1960's to 2018 *Proc. 2nd African Int. Conf. on Industrial Engineering and Operations Management Harare* (*Zimbabwe*, *7–10 December 2020*) pp 1347–58
Smil V 2017 Energy transitions: global and national perspectives (expanded and updated edition) vol 30 p 297
Tambari I T, Dioha M O and Failler P 2020 Renewable energy scenarios for sustainable electricity supply in Nigeria *Energy Clim. Change* **1** 100017
Taylor I 2018 The transfer of power and the colonial legacy *African Politics: a Very Short Introduction* pp 25–38
THE PUNCH 2020 MAN flays move to ban importation of generators (Punch Newspapers) (available at: https://punchng.com/man-flays-move-to-ban-importation-of-generators/#google_vignette) (Accessed 15 December 2024)
Tongwane M I and Moeletsi M E 2021 Status of electric vehicles in South Africa and their carbon mitigation potential *Sci. Afr.* **14** e00999
Twesigye P 2022 Structural, governance, & regulatory incentives for improved utility performance: a comparative analysis of electric utilities in Tanzania, Kenya, and Uganda *Util. Policy* **79** 101419
Tyre World 2024 How much does it cost to own an electric vehicle in Africa? | by tyre world | nov, 2024 | medium (Medium) (available at: https://medium.com/@MadAboutMachine/how-much-does-it-cost-to-own-an-electric-vehicle-in-africa-a579323d1319) (Accessed 21 November 2024)
UNEP 2020 *Used Vehicles and the Environment—a Global Overview of Used Light Duty Vehicles: Flow, Scale and Regulation*
UNEP 2023 Integrating electric 2&3 wheelers into existing urban transport modes in developing and transitional countries: Uganda (available at: https://sustmob.org/EMOB/pdf/230928_BMU-IKI_UgandaProjectBrief_Final.pdf) (Accessed 18 November 2024)
United Nations Department of Economic and Social Affairs P.D 2022 World population prospects 2022: summary of results UN DESA/POP/2022/TR/NO p 3
USAID 2024 Examining energy efficiency issues in Sub-Saharan Africa | archive—U.S. (Agency for International Development) (available at: https://2012-2017.usaid.gov/powerafrica/newsletter/dec2014/smarter-power-in-africa) (Accessed 19 November 2024)
Voronoi 2024 African Countries' GDP per capita mapped—Voronoi (available at: www.voronoiapp.com/economy/African-Countries-GDP-per-Capita-Mapped-1362) (Accessed 21 November 2024)
World Bank 2019 *The Dirty Footprint of the Broken Grid: the Impacts of Fossil Fuel Back-up Generators in Developing Countries*
World Bank 2024 Poverty, prosperity, and planet report 2024 (available at: www.worldbank.org/en/publication/poverty-prosperity-and-planet) (Accessed 15 December 2024)
Wu Q, Chang S, Bai C and Wei W 2023 How do zombie enterprises hinder climate change action plans in China? *Energy Econ.* **124** 106854