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ISSUE BRIEF

A path across the Rift

Informing African energy transitions by unearthing critical questions and data needs

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Issue briefs focus on policy issues, and clearly draw out the implications of existing evidence for decision makers.

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HIGHLIGHTS

- The low-carbon opportunity is widely recognized within Africa, but there is still an urgent need to develop clear visions for the future of Africa's electricity and energy systems and what it will take to deliver them.
- The body of analysis on African energy transitions has been growing, but struggles to influence decision-making, due in part to low resolution, limited contextualization, a broad science-policy gap, and limited or no ownership.
- The debate on African energy transitions among both local and international stakeholders has become increasingly polarized, narrowing the space for fact-based discussion on key topics, such as the role of fossil fuels.
- There is an urgent need to ensure that decisions on African energy transitions today are informed by clear and objective analysis, ideally undertaken at the country level.

EXECUTIVE SUMMARY

The debate over Africa's energy future

The debate over necessary growth of Africa's energy systems, and the future role of fossil fuels in the context of global energy transitions, has become polarized. Discussions on African energy transitions are characterized by reductive narratives, divergent viewpoints, and well-meaning but misguided searches for one-size-fits-all solutions. As a result, climate, diplomacy, and development goals may be compromised. Africa's leading institutions in this debate have clearly articulated the urgent need for data and evidence.

Africa's role in the global energy transition is unique as the least-electrified continent with the fastest-growing population. Enabling prosperity for this growing population through expanded access to modern forms of energy and industrialization will require at least a tripling of power supply by 2030, according to the International Energy Agency (IEA 2022a). Thus, the continent's energy systems, which stand underdeveloped and severely underresourced today, warrant close attention.

At approximately 80 GW of installed capacity, sub-Saharan power system capacity is less than one-quarter of India's. African energy transitions are thus less about moving away from fossil fuels, but rather about how to rapidly expand power generation in reliable, resilient, and affordable ways while remaining climate-compatible and ensuring access for all. Because every African country has a different starting point (Mulugetta et al. 2022), energy road maps for African countries cannot be a single narrative; yet they are often presented as such.

Africa's energy transitions and the role of fossil fuels such as gas have become a polarizing debate because of the following multiple factors characterizing African energy transitions:

- The difficulty of securing investment from the international finance community to expand renewables on the continent
- The challenges of delivering large shares of electricity through intermittent renewable resources against the backdrop of weak power systems
- The challenge of electrification of a mostly secondhand vehicle fleet and a household sector that relies largely on traditional biomass
- The relatively low historical exploitation of the continent's fossil fuel resources when compared to Global North countries (leading to diverging viewpoints on the fairness of imposing energy transitions on African countries)
- The continent's growing industrialization agenda, which requires feedstocks that do not yet have economically viable low-carbon substitutes in all cases

Debate-style interaction tends to reduce complex issues that warrant nuanced dialogue into high-level talking points or arguments. Such arguments may be simple to understand ideologically, but they may not provide the substantive evidence necessary for good decision-making. In a vacuum of comprehensive and digestible data, reductive narratives risk predetermining Africa's options (Mulugetta et al. 2022). The risk urgently requires mitigation. Energy transition decisions and policy determined now will carry weight going forward, with near- and long-term implications for economic trajectories, international partnerships, trust, and multilateralism, and, moreover, the prospects of millions for attaining prosperity.

About this issue brief

Africa's leading institutions in this debate, such as the African Union Commission and the United Nations Economic Commission for Africa (UNECA), have clearly articulated the urgent need for data and evidence (African Union Commission 2021; UNECA 2020). In response to this call, WRI Africa and the Energy Transition Commission (ETC) formed a partnership on targeted research and high-level engagement. WRI Africa and ETC recognize the need to bring a factual base to the discussions and to highlight critical unanswered questions that decision-makers must consider when formulating holistic perspectives about transition pathways.

This Issue Brief reviews the available analyses of African energy transitions to unearth the critical open questions that require answering to enable science-based policy-making. Through this review, we identify a clear set of open and, as yet, unanswered questions on African energy transitions, in particular pertaining to sub-Saharan Africa (SSA), outside of South Africa.

Open questions that must be answered

The identified open questions relate to distinct issues on the financial, technical, and economic level. They scale from individual projects to the electricity sector, the wider energy sector, and the whole economy.

- What is the real cost of renewable electricity generation technologies, considering the relatively high cost of capital across SSA, and what does this mean for cost-optimal electricity mixes?
- How could electricity grids in SSA improve their stability beyond current (often inadequate) levels while expanding electricity access and absorbing high shares of variable renewables?
- How can electricity demand grow sustainably to avoid over- or undersupply, in a context of high numbers of future consumers with low electricity bills waiting to be connected?
- What are viable pathways toward universal clean cooking access, clean transportation fleets, and clean industrialization?
- What are the effects of global market forces on countries that continue to rely on, or hope to develop, fossil fuel economies in a decarbonizing world, and what are the green alternatives that exist?

Key findings

We find that the literature so far has provided insufficient answers, leading to a gap between research results and what policymakers across SSA need to plan for a clean energy transition. One overarching problem stands out for SSA: Most published research is done at the continental level with little regard to country-level pathways that would be of more use to policymakers across the African continent. If this focus on the continental level persists, the reductive narratives and misguided searches for one-size-fits-all solutions will continue to complicate the debate on African energy transitions.

We note differences between the key models currently informing the debate and the reality on the ground. Our approach helps identify blind spots in research, uncertainties in assumptions, and variables of high sensitivity in transition pathways. Such insights lead to a sequence of clear "no regrets" actions on which there appear to be consensus and, conversely, gaps in evidence requiring urgent attention as next steps.

- Projections of the scale and pace of clean energy expansion in each African country will depend on variables like the cost of capital, investment flows, and levels of grid reinforcement. Existing models often underemphasize these important variables, contributing to contentions among stakeholders and leaving research results open to interpretation and/or criticism.
- Increasingly viable technologies that may offset the need for fossil fuels in industry (e.g., in steel and fertilizer) warrant deeper research. At the same time, the limits of clean alternatives in cooking, cement making, and transportation will need to be acknowledged to achieve energy transition planning processes rooted in realism.
- Ultimately, best projections of future demand suggest that further exploitation of Africa's oil and gas resources will not "blow the global carbon budget," as some have suggested (Goldstone 2021). However, important questions exist around the financial risks attached to an expansion of oil and gas infrastructure in various African countries in the context of a decarbonizing world. Further, international trends suggest that comparable revenue-generation streams from green hydrogen and critical minerals expansion may become feasible for several African countries, warranting the production of country-specific scenario analysis and a ramping up of technology transfer.

Our goal is that this synthesis can directly inform the ongoing debates and dialogue, helping to defuse areas of contention through objective and unbiased data presentation.

THE DEBATE OVER AFRICAN ENERGY TRANSITIONS AND OUR APPROACH

Why African energy transitions are unique

In the context of planning for clean energy transitions, the African continent occupies a unique position: It simultaneously has the fastest-growing demand for modern forms of energy and the lowest rates of access to modern forms of energy (IEA 2022c). Africa's population growth rate is more than double the world average at around 2.5 percent annually (UN 2022), but access to electricity stands at only 43 percent and access to clean cooking at a mere 17 percent (IEA 2022b). These trends are particularly prominent in SSA, with the notable exception of South Africa. Any growth path should thus start from the basis that African electricity and energy use per capita will and must grow rapidly to reach many times its current level.

The term *transition* is perhaps a misnomer. The word implies changing an existing system from one condition to another, but what if most of the system has yet to be built? Rather than a *transition*, most SSA countries are poised to experience considerable and much-needed energy system *expansion*.

The challenge is therefore not to achieve a shift away from fossil fuels but to develop clean energy growth to build up low-carbon economies.

Energy pathways across the African continent are characterized by their multidimensionality. Energy in SSA is intrinsically linked to questions about industrialization agendas (which advanced markets have largely already achieved on the back of fossil fuels), improving public health (often related to the prevalence of cooking based on traditional biomass), achieving financial health for utilities (currently the exception rather than the rule), increasing electrification speed (with population growth having historically mostly outpaced the growth in access to electricity), and others.

These unique features of energy systems across SSA have consequences for short- and long-term planning and have led to diverging views and approaches. This divergence can be seen in the disparity among scenarios on African energy transitions developed by various authoritative African and non-African organizations in recent years.

Divergent viewpoints on African energy transitions

Globally, it is widely accepted that the pathway toward decarbonizing energy use rests on massive electrification of end-uses, alongside a buildout of infrastructure to generate and transport electricity from low-carbon sources—mostly solar PV and wind power—while moving toward alternative fuels in hard-to-electrify sectors like heavy industry—for example, green hydrogen (Eurelectric 2018; IRENA 2017, 2018a, 2022a; IRENA and State Grid Corporation of China 2019).

The African continent, which has among the best solar and, to a lesser extent, wind resources worldwide (Sterl et al. 2022), thus appears well-positioned to grow its energy systems based on high shares of renewables from the outset (Sterl 2021a, 2021b). On paper, many SSA countries are basically greenfields for planning renewables-based electricity systems and electrified end-use sectors. Recent analysis from the IEA Africa Energy Outlook (IEA 2022a) and the International Renewable Energy Agency (IRENA) World Energy Transitions Outlook (IRENA 2022c) corroborate this viewpoint. The reports showcase that most, if not all, African countries could and should rapidly transition to renewables-based electricity systems and minimize the buildout of new fossil fuel infrastructure. Some political leaders have echoed this statement; for instance, Kenya's last two presidents have affirmed the target of transitioning to 100 percent clean energy by 2030 (Kuhudzai 2022).

But other organizations, experts, and political leaders argue that Africa should do the opposite and focus on developing its substantial oil and gas resources for industrialization and export earnings, and (in the case of gas) power generation. This viewpoint has been propagated by, among others, the African Energy Chamber (AEC 2020), the Africa Finance Corporation (AFC 2022), and UNECA (Al-Zu'bi et al. 2022; UNECA 2020). These institutions believe that gas will have to play a substantial role in domestic energy systems and that oil and gas exports could provide much-needed export revenues to countries with available reserves. The idea that African countries should welcome further investments in fossil fuel infrastructure has been echoed by several political leaders, such as the presidents of Senegal (Koc et al. 2022) and Niger (*Le Figaro* 2022). However, some of the recent excitement around oil and gas exports came in the wake of Russia's illegal invasion of Ukraine, when it looked as if Europe might be in danger of acute gas shortages. However, European countries managed unprecedented reductions in gas demand and replaced the Russian supply with (non-African) alternatives before the onset of winter (European Commission 2023).

The debate on fossils versus renewables represents one of many divergences, uncertainties, and blind spots in African energy transition pathways. Other examples include unaccounted-for differences in the cost of capital among countries (Agutu et al. 2022), the blind eye turned to future grid reinforcement needs, the typical simplification of Africa as a generic collection of similar countries with comparable circumstances, and the absence of credible demand growth projections. Some examples of unhelpful key refrains on African energy transitions are given in Box 1. Given the overall lack of energy modeling studies focusing on individual SSA countries—with most SSA countries not having a single peer-reviewed study on the topic of energy-system decarbonization dedicated to them (Oyewo et al. 2023), and with the existing studies often not co-created with local stakeholders—there is a danger that such unhelpful refrains will dominate debates around policymaking at the expense of science-based information.

Approach and methods

We reviewed existing studies on energy pathways for African economies to identify the main open questions that require answering to harmonize the polarized viewpoints on African energy transitions. The scope of the review covered academic and gray literature, the latter typically from international organizations like the IEA, IRENA, and the World Bank. Reviewed studies date mostly from the last decade, during which the topic of energy transitions rose high on the international agenda. We mainly focused on studies that used cost-optimization models to develop pathways for African energy transitions.

The review focused on identifying the main open questions concerning issues in African energy transitions that are relatively specific to the African context. These issues are low electricity access rates, low reliability of existing electricity systems, low base of installed capacity, high rates of expected energy demand growth, low baselines in terms of energy demand in transportation and industry, and high use of traditional biomass by households.

BOX 1

Unhelpful clichés on African energy transitions

Visions of African energy transitions are riddled with unhelpful romanticisms, oversimplified narratives, misguided searches for one-size-fits-all silver bullets, contradictory statements, and paternalistic viewpoints. A few examples are provided below.

Romanticized visions

"*(...) many commentators now believe that Africa is primed for (...) bypassing decades of energy infrastructure expenditure and creating a renewable, off-grid energy system.*"—DWF Group

"*Sun, wind, big rivers and ancient volcanoes. All in abundance. The Africa of renewable energy is a land full of potential.*"—Enel Green Power

Silver-bullet solutions

"*If it were ever built, it [Grand Inga Dam in the DRC] would generate (...) enough to light up South Africa, the continent's most industrialised country.*"—*The Economist*

"*Africa could supply the whole world with affordable low-carbon energy in the form of hydrogen, a new report suggests.*"—WEForum

Contradicting statements

"*To minimise the adverse effects of climate change, hydropower is needed to enhance Africa's resilience to climate change.*"—IEA

"*African hydropower is particularly vulnerable to climate change due to its sensitivity to water availability which is often restricted.*"—IEA

Paternalism

"*The future (...) for Africa is one of green power. The continent has 'one of the world's best renewable energy potentials' combined with comparatively low energy consumption.*"—EURactiv

Sources: DWF Group 2018; Enel Green Power 2018; *The Economist* 2017; EURactiv 2022; IEA 2020b; WEForum 2022.

Four principal questions

We identified several main scales of open questions, from project-level and grid-level techno-economics, across demand prospects for electricity and non-electrified energy, up to the role of energy commodities in the export market (Figure 1). This allowed us to organize the key uncertainties on African energy transitions into a succinct structure comprising four overarching questions.

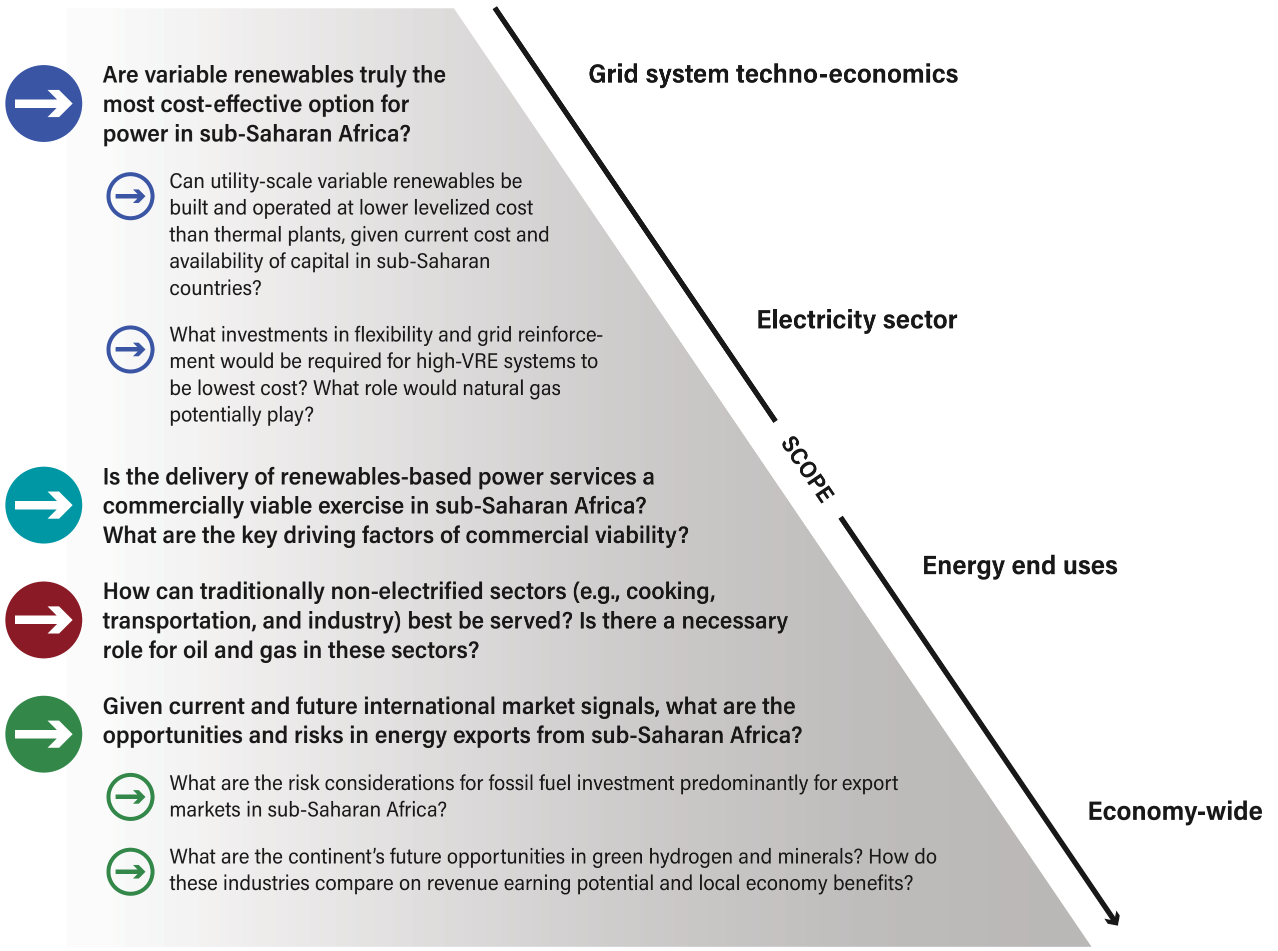
The rest of this brief is structured under each of the four questions. Existing positions are laid out, conflicting viewpoints are explained and examined to find any critical open questions, and areas of emerging consensus are synthesized to indicate no-regrets decisions.

ARE VARIABLE RENEWABLE ELECTRICITY (VRE) SOURCES TRULY THE MOST COST-EFFECTIVE OPTION FOR ELECTRICITY GENERATION IN SUB-SAHARAN AFRICA?

We begin by looking at African countries' options for expanding generation and delivery of electricity. Recent years have seen a paradigm shift in thinking around the potential role of VRE resources that is, those whose yield depends on weather conditions, such as solar PV and wind power. It used to be believed that power systems need substantial baseload power from plants with large synchronous generators and cannot absorb levels of VRE beyond 10–20 percent, but recent evidence from

FIGURE 1

Four main areas of questioning that are critical to developing perspective on options for African energy transitions



Source: Authors.

countries like Germany, Portugal, Denmark, and Uruguay has proved otherwise (IRENA 2015). There are now multiple examples of grid systems progressively increasing their average share of VRE and even running at or near 100 percent VRE for prolonged periods. This shows that baseload may be an outdated concept and that we rather need to plan for systems with sufficient *flexibility* (IRENA 2018a; Lovins 2017). The emerging consensus is that high-VRE systems could be well balanced with a combination of dispatchable plants and storage solutions (Bogdanov et al. 2019; Gulagi et al. 2022; Jacobson and Delucchi 2018; Ram et al. 2019).

Regarding economics, there is general consensus that, globally, solar PV and wind power are well on the way to displacing fossil fuels and hydropower as the cheapest technologies for generating electricity (IRENA 2022b). The cheapness of power generation is often measured through the levelized cost of electricity (LCOE): the cost per unit of electricity generation that offtakers would need to pay a project developer for the project to break even across the project's lifetime. This LCOE has, on worldwide average, fallen by 90 percent for solar PV, 67 percent for onshore wind, and 60 percent for offshore wind over the last decade (IRENA 2022b), reaching values toward the low end of or below the typical range for fossil fuel-based power generation. Costs are likely to continue to fall over the medium term, notwithstanding possible short-term increases linked to, for instance, supply chain bottlenecks (BNEF 2022). Emerging research also appears to suggest that largely VRE-based power systems for Africa are a technically conceivable and economically attractive solution (Barasa et al. 2018; Bogdanov et al. 2019; Sterl and Thiery 2022). While relatively few countries have successfully embarked on aggressive pathways toward higher VRE integration, some recent examples offer positive outlooks. Uruguay, for instance, was able to grow the share of VRE in its power system from nearly zero to almost 50 percent between 2013 and 2020 (IEA 2020a).

Given that Africa has among the best-quality renewable resources in the world, a common narrative nowadays is that Africa could "leapfrog" or "bypass" the era of fossil fuels and go straight to renewables (see Box 1). But does this hold true? While the research cited earlier seems to imply that it could work out in theory, there are important criteria unaccounted for in many modeling studies that determine the reality.

For instance, while resource quality in combination with declining technology costs is a useful starting point, other factors help determine the true cost of technology. One missing piece of analysis is whether the costs of capital—reflecting the risks deemed acceptable by prospective investors and which factor into the calculation of any LCOE—for VRE projects in SSA are accurately reflected in the proposed pathways and how this affects the competitiveness of solar and wind power plants. Another missing piece concerns the need for grid reinforcement, given the fact that many power grids in SSA are currently suffering from stability problems *even without* substantial VRE feed-in. Both points are addressed as follows.

Can utility-scale VRE be built and operated at lower levelized costs than thermal plants, given the current cost and availability of capital in sub-Saharan countries?

It is tempting to assume that VRE generation would be cheaper in SSA than in many other parts of the world, given that Africa receives the highest levels of solar irradiation of all continents (Global Solar Atlas 2020), several regions have excellent wind resources (World Bank Group 2020), and (on paper) plentiful land is available that could house solar and wind power plants without competing with other land uses (Sterl et al. 2022).

However, LCOE estimates depend crucially on assumptions about the cost of capital, also referred to as Weighted Average Cost of Capital (WACC) (Agutu et al. 2022). The LCOE generally considers up-front capital expenses (CAPEX), operation and maintenance costs (OPEX), and fuel costs. Solar and wind projects are CAPEX-heavy in nature: Most costs are incurred up front in capital investment, with low subsequent operating costs and zero fuel costs. In this, solar and wind projects differ crucially from fossil-fuel power plants. Consequently, the LCOEs of solar and wind power are much more sensitive to increases in the cost of capital than the LCOEs of fossil fuel-based plants (Egli et al. 2019; Sweerts et al. 2019).

Most energy modeling studies on Africa do not reflect the wide range of costs of capital observed and sometimes assume lower costs of capital than those reported for individual countries. The Sustainable Africa Scenario from the IEA (IEA 2022a) assumes a 7 percent WACC, and IRENA assumes 10 percent across the board in several of its Africa-focused studies (IRENA 2018b, 2021b); and while a recent scientific paper on African energy pathways assumed WACC to decline over time, it did not consider differences among countries (Oyewo et al. 2022). However, estimated WACC values can differ widely among countries. Recently, IRENA published estimated real WACCs at country level, based on a survey- and interview-calibrated benchmarking tool (IRENA 2023b). Values range from 1 to 20 percent across developed and developing countries—but crucially, only from 1 to around 5 percent in the most developed economies. A recent scientific paper (Agutu et al. 2022) corroborates this disparity and finds a WACC range of 2.6 to 18.5 percent in sub-Saharan Africa. Thus, depending on the specific country context, the actual LCOE for VRE may remain substantially higher in some African countries than the LCOE for fossil fuel-based plants, despite the numbers in many Global North countries already favoring VRE.

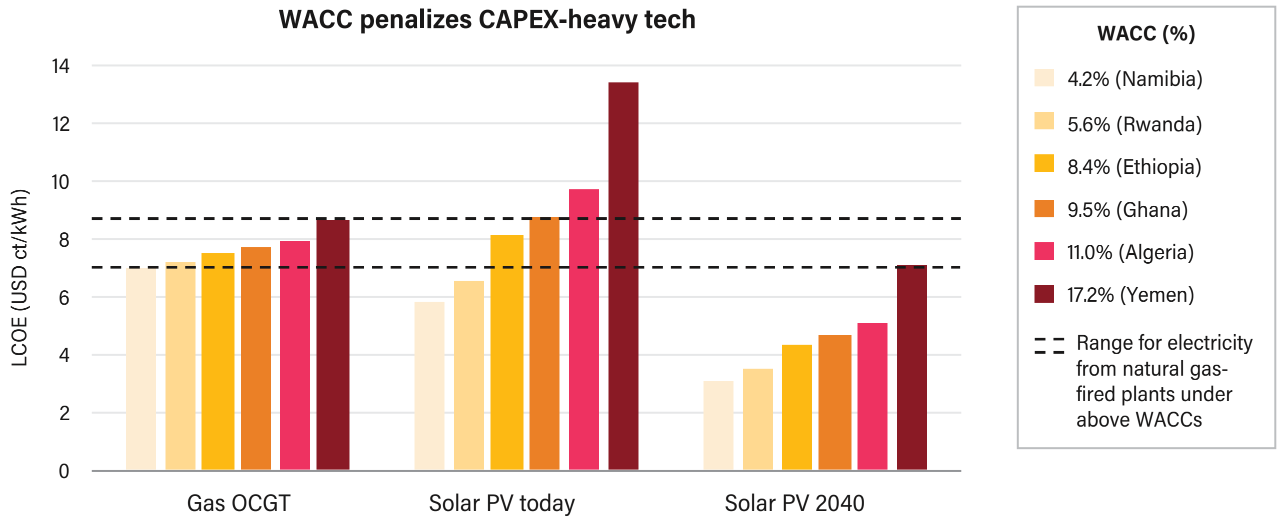
We provide illustrative examples using IRENA's WACC estimates for several African countries in Figure 2. Even under assumptions of strong continued decreases in the CAPEX and OPEX of solar PV plants, it is not guaranteed that solar PV will become cheaper than natural gas plants before 2040 in countries where the cost of capital is very high, such as countries suffering from ongoing conflicts. (We use Yemen as an example of such a country in the absence of African examples in the IRENA database.)

WACC values diverge at the country level because of perceived risks related to overall political stability, policy environments for investments, coherence of countries' power sector planning strategies, the state's capacity to implement, vested interests, corruption, and currency risk (with loans and equity investments typically done in internationally traded currencies, but revenue streams occurring in local currencies). In other words, when projects face a multitude of such risks, these are priced into the cost of capital provided by investors (IRENA 2022b).

A reasonable hypothesis is therefore that solar and wind could and should be lower-cost sources of electricity than fossil fuels in most SSA countries, but only if the cost of capital can be reduced through appropriate de-risking. The most appropriate de-risking measures may differ across countries—hence the importance of finding shared visions on policies, governance reforms, public investments or incentives or guarantees, data transparency, and so on that would help reduce WACC values. Such financial dynamics are typically not considered in the modeling analyses on African energy transitions undertaken by international bodies and in academic literature.

FIGURE 2

CAPEX-heavy technology, like solar PV, is penalized under increasing WACC as compared to natural gas



Notes: Here, we compare gas OCGT plants to solar PV plants at 2020 costs ("today") and at projected 2040 costs under different WACC values as per IRENA.

Sources: All values on CAPEX, OPEX, and fuel costs are taken from IRENA (2021b) and expressed in 2015 U.S. dollars; we used the 2015 fuel costs for natural gas from the same source. Other assumptions included a 35-year lifetime for OCGT plants and a 30-year lifetime for solar PV (Oyewo et al. 2022), a 40% efficiency and 50% average capacity factor for OCGT plants, and a 19% average capacity factor for solar PV plants. (The CF of solar PV differs from country to country, although typically by a few percentage points at most [Sterl et al. 2022]). The WACC values represent the real (inflation-adjusted) 2021 numbers for solar PV on a country-by-country level, and are taken from IRENA (2023b).

The quantity of capital available will matter as much as the cost. Total financial flows per capita supporting the development of SSA power systems are currently far smaller than those observed in other developing countries: less than $25 in 2019, compared to approximately $170 in India and Bangladesh (SE4ALL and CPI 2021). Average annual flows of investment from both private and international sources in access to electricity and clean cooking across the African continent are currently only around one-tenth of what would be needed to achieve universal access by 2030 (IEA 2022a).

On the other hand, public and private funding for fossil fuel investments may become restricted as developed economies seek to ensure that their commitments to reduce domestic emissions are not offset by financing carbon-intensive technologies elsewhere. Major private-sector financial institutions that have set net-zero targets are seeking to reduce fossil fuel finance and will be increasingly unwilling to finance fossil fuel projects in SSA (UNFCCC 2021). The G7's announced pledge to end "new direct public support for the international unabated fossil fuel energy sector" is another example (*The Economic Times India* 2022). This trend toward decreasing availability of finance for fossil fuel projects may somewhat counteract the penalty of high WACCs on VRE technologies.

Commitments to limit fossil fuel investment will still need to be matched by strong commitments to provide sufficient and affordable financing for VRE systems if VRE is to be a feasible low-cost route to rapid electricity system growth.

What investments in flexibility and grid reinforcement would be required for high-VRE systems to be lowest cost?

What role would natural gas potentially play?

The cost of installed generation is only one component of energy systems. Electricity generation should not only be cheap, but also reliable. This is where the "V" in VRE comes in: The sun does not always shine, and the wind does not always blow. No matter how low the LCOE of a solar PV plant, the plant will be of little use during nighttime.

Electricity supply and demand need to be balanced across the full range of time periods: from balancing frequency and voltage on a second-by-second basis to ensuring adequacy of electricity supply across hours, seasons, and years. Fortunately, the hourly, seasonal, and interannual dynamics of power generation from VRE in Africa have already been rigorously studied by academia. A viewpoint is emerging where solar PV with battery storage could become the backbone of SSA's power systems (Barasa et al. 2018; Bogdanov et al. 2019; Oyewo et al. 2022). Solar would be backed up by wind and flexible hydropower where available (Oyewo et al. 2020; Sterl et al. 2020, 2021) (with elegant hourly and seasonal synergies in many cases). Gas would be a transition fuel where no other options are available, aided by the drive toward higher regional interconnections, primarily through power pools and the design of an African Single Electricity Market (African Union 2021; IRENA 2018b, 2021b; Sterl 2021a; Wu et al. 2017). However, the available academic analyses typically do not include power flow analysis and tend to gloss over the grid stability question.

Developed world power system operations have already seen many days where VRE provides close to 100 percent of electricity (EEA 2017), proving that very short-term balancing challenges at high VRE infeed is technically manageable. However, this evidence comes from countries that already have large-scale adequate grids with sufficient flexibility. In SSA, many countries are working with small and often unreliable power grids.

The buildout of VRE plants across the developed world, with adequate grids as starting point, allows countries to gradually move from low to high VRE shares, readying the system and increasing flexibility along the way.

As the first set of VRE plants was deployed in many countries, their impact on stability was insignificant at the system level; effects were localized, for example, at the plants' grid connection points (IEA 2020c). As VRE shares grew, countries could typically call on existing flexible resources before reaching levels that required more advanced flexibility measures (e.g., through storage and demand response).

Conversely, in many SSA countries with low power generating baselines, utility-scale VRE plant deployment will require power systems to traverse the different stages of VRE integration considerably faster. A solar PV plant of a given size would lead to a much larger jump in VRE share on the power grid of, say, Niger (with an existing capacity of a few hundred MW) than in the Netherlands (with only 70 percent of Niger's population but several tens of GW installed). In addition, even VRE shares of approximately 10 percent can lead to problems on small grids with low inertia without adequate additional measures like including battery storage as a standard component of VRE power plants (Chen et al. 2020). In addition, many African countries' grids suffer from reliability problems even in the absence of high VRE infeed (J.T. Lee and Callaway 2018).

Again, we must stress the importance of the individual country context. In some African countries, especially those with a strong basis of hydropower generation (e.g., Ethiopia), grids may already have sufficient existing inertia and flexibility to allow a relatively rapid scale-up of VRE integration without causing (or exacerbating) stability problems (Sterl et al. 2021). Others would require substantial reinforcements or interconnections to neighboring countries before such scale-ups could be feasible (Sterl 2021a).

Broad grid reinforcement strategies will be required to ensure that SSA's burgeoning power grids can absorb high levels of VRE, and existing analyses have not yet clearly identified the additional costs and how they differ by country. Over the past decade, only 0.5 percent of investment for African power systems went into transmission (99.5 percent went into generation). The IEA suggests that transmission might need a share as high as 40 percent, highlighting the urgent need for a major shift in investment allocation (ESI Africa 2022; IEA 2022a). Recent ETC research suggests that the needs may be even higher for sub-Saharan Africa and that a net-zero transition would require every unit of investment in electricity generation to be matched by 1.5 units in grid investment (ETC 2021a).

While the need for substantial grid investment would apply to both fossil-based and renewables-based grid buildout, the specific nature of VRE has a range of impacts on power systems the implications of which for grid expansion planning differ from those of fossil fuels (Heptonstall and Gross 2021). The silver lining in this historical lack of investment in grid infrastructure is that many African countries have a unique opportunity now to build out VRE-based grids from the outset, given that lock-in to fossil-based grid infrastructure is still limited (Sterl 2021a).

Detailed country-level analysis is essential to identify how the grid expansion, reinforcement, flexibility, and stability needs of high-VRE systems might best be met; what the costs would be; and to what extent gas would be needed as a near- and medium-term transition fuel providing various ancillary services (Mulugetta et al. 2022). Such country-level analysis is currently hard to find for SSA, with many countries not having a single academic study on clean energy transitions dedicated to them (Breyer et al. 2022; Oyewo et al. 2023). Research has so far focused on providing continent-level pictures of optimal energy transition pathways (Barasa et al. 2018; Ouedraogo 2017; Taliotis et al. 2016).

Recently, the gap has been partially filled by organizations like IRENA and the International Atomic Energy Agency with dedicated studies, for example, for Gabon (IRENA 2021a; Anvane-Obame et al. 2019) and Niger (IRENA 2021c), but even these studies did not cover the timescales relevant for frequency and voltage stability. While it is true that grid stability studies were historically often done by the system operators themselves, not the academic community, the link between capacity expansion studies and grid stability studies does not seem to have been made for most of the studies on the expansion of African country-level power systems cited above. The danger is that conclusions on grid reinforcement needs will be drawn prematurely.

Synthesis

Renewable resources are abundant across Africa and should theoretically be low-cost. High penetration of VRE in power systems is technically feasible, as demonstrated by various countries worldwide; and it could be cost-optimal to prioritize VRE in the expansion of power systems, as much of the scientific literature on African and non-African countries suggests. However, many important factors on the ground—investment risk affecting the cost of capital, weak existing grids requiring substantial reinforcement to allow absorbing even relatively low shares of VRE, and investment into grid expansion lacking, as compared to power plant construction—create a substantial gap between energy transitions suggested in the literature and the reality of most African countries. Existing models often underemphasize these important variables.

African countries will need specific forms of financial support for de-risking and public and private investment, leveraged domestically and from the international community in both power generation and grid reinforcement and buildout, to realize the full technical potential that clean energy technologies offer. Unless these are realized soon, the energy transition in Africa may fail (Alova et al. 2021).

IS THE DELIVERY OF RENEWABLES-BASED POWER SERVICES A COMMERCIALLY VIABLE EXERCISE IN SSA?

WHAT ARE THE KEY DRIVING FACTORS OF COMMERCIAL VIABILITY?

Renewables-based electricity systems for sub-Saharan African countries will require large amounts of up-front investment in generation and infrastructure to transport electricity. Because the return on these investments will eventually come through electricity bills paid by end users, both at the household and the commercial or industrial level, there is a strong link between end-use electricity demand and investments in the electricity system. Power system expansion models typically assume a certain exogenous demand and calculate the optimal technology portfolio to meet this demand. But as we argue here, for countries in SSA with substantial latent demand, this leaves several important questions unanswered.

Current per-capita electricity generation in SSA is extremely low by international standards—estimated at around 200 kWh/capita/year—and projections from IRENA and the IEA forecast an increase only to 500–700 kWh/capita/year by 2030, even under assumptions of universal access for households (IEA 2022a; IRENA 2020). For comparison, current per-capita annual generation is around 5,400 kWh in China and around 1,100 kWh in India (Our World in Data 2022).[1] The projections for Africa therefore assume that most end users remain in very low tiers of electricity consumption once access is achieved and that commercial and industrial customers are relatively few or small.

Surveys of power utilities indicate that one of the key barriers to improving electricity access is the cost of connecting customers to the grid (PwC Africa Power and Utilities Sector Survey 2015). In situations where large numbers of households have low levels of power consumption, the cost to connect them may be prohibitive as the costs of new connections may not be recouped through electricity bills within viable time frames (K. Lee et al. 2016). In other words, connecting customers with low electricity bills to the grid may not be a financially viable exercise for African utilities.

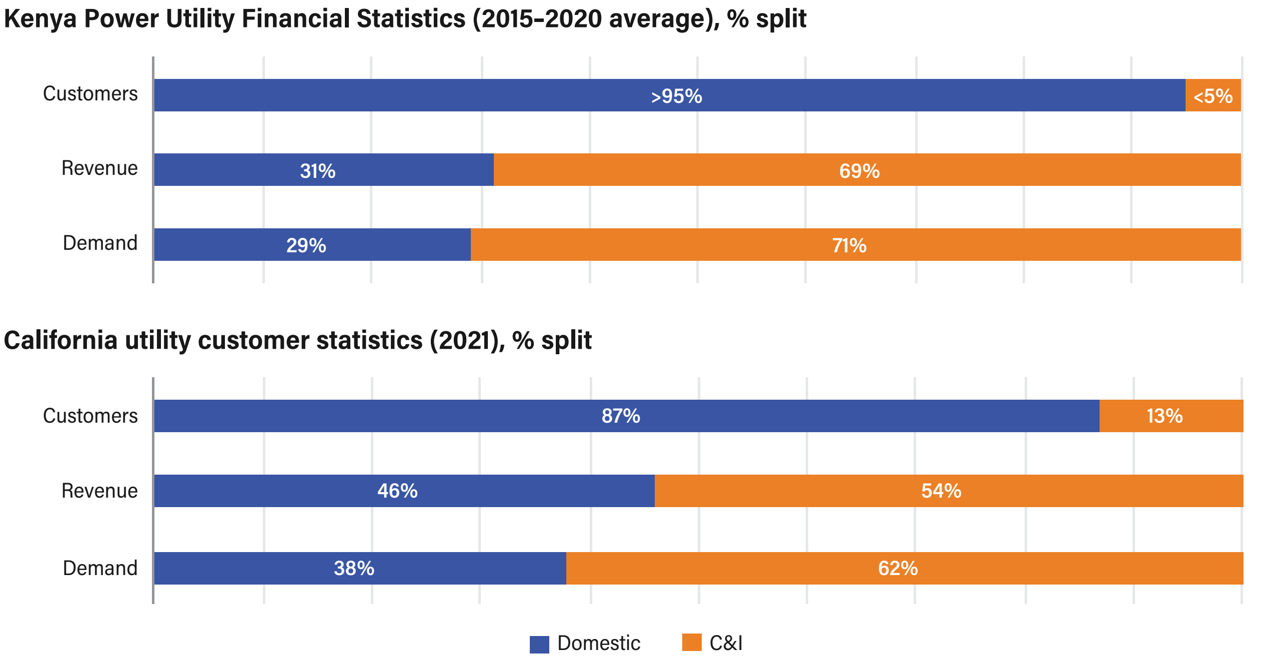
As a consequence, utilities in SSA are highly dependent on a small number of commercial and industrial (C&I) customers to keep them afloat financially. This affects both their ability to reinvest in grid upkeep and reinforcement and the bankability of utility-scale power generation projects the offtaker of which would be the utility. Many SSA utilities are not in good financial health (Trimble et al. 2016; Twesigye 2022): As of 2018, only one-third of African utilities were able to recover their operating and debt-service costs, and this was further exacerbated by the COVID-19 pandemic (Balabanyan et al. 2021).

The utilities' financial dependence on the C&I customer segment in SSA means that growing this segment is critical to provide the revenue needed to invest in grid strengthening and expansion. And while the situation of a relatively small number of customers supporting a utility's revenue base is not unique to sub-Saharan Africa (Figure 3), two unique factors affect SSA utilities: the pressure to expand electricity access (which is not an issue in the Global North) and low grid reliability, potentially scaring C&I customers away from using grid electricity and thus exacerbating existing pressures.

There are thus two critical questions for countries in SSA in the context of sustainable demand and supply growth. The first is how the C&I sectors can grow while avoiding the utility death spiral in which utilities that are supposed to be floated by the tariffs paid by C&I customers are unable to provide those customers with reliable power 24/7, leading to those same customers turning to other sources (e.g., on-site generation), further reducing the utility's income and capacity to provide reliable power. A key element might be what can be done for those coun-

FIGURE 3

Relative share of household (domestic) and commercial and industrial (C&I) customers of utilities in Kenya and California: number of customers, revenue, and demand



Source: Data for Kenya from Kenya Power 2021 and for California from EIA 2022.

tries where this death spiral is already established. For instance, what could the international finance community do to intervene in countries where the utility is trapped in a negative feedback loop of losing key C&I customers and dropping revenues, thus remaining unable to invest in expanding access and improving quality of delivery?

The second question is how domestic offtake of electricity can grow in line with development objectives without placing undue financial burdens upon struggling utilities (for instance, by insisting on connecting large numbers of low-bill customers). Mini-grids and standalone systems might play an important role (Lucas et al. 2017; Mentis et al. 2017). At low levels of electrification, such systems can be more-cost effective than connecting households to a utility-scale grid, especially if they are located relatively far from that grid and if their consumption levels are low (Lucas et al. 2017). Developing off-grid systems could provide initial "bundles" of electricity access to households in the lower tiers (ESMAP and SE4All 2015), with eventual connection to the grid following as these households move up the tiers of electricity use. The approach would reduce the burden on the utility to provide initial access. (In the mini-grid space, appropriate business models involving domestic and commercial customers are of course also key to ensuring financial viability.) Policymakers should consider actively speeding up these types of innovation through policy incentives for off-grid systems (Trotter and Brophy 2022). Again, the promise of such systems will differ across countries, as will the challenges of economics and financing. More research on these topics at the country level will be of high importance for African energy transitions.

Expanding electricity access across SSA is more than a question of assuming a certain demand growth and figuring out the lowest-cost technology mix to meet this demand, as most energy modeling studies do. The specific nature of how utilities operate has an impact on the speed and extent to which expansion of electricity access can take place, and growing and strengthening the C&I segment across SSA will be crucial to the financial health of utilities that must undertake such expansions. This demand-side view has not yet been covered in detail in authoritative studies on African energy transitions.

HOW CAN TRADITIONALLY NON-ELECTRIFIED SECTORS (E.G., COOKING, TRANSPORTATION, AND INDUSTRY) BEST BE SERVED?

IS THERE A NECESSARY ROLE FOR OIL AND GAS IN THESE SECTORS?

We have argued that it is conceivable that expanding access to reliable electricity across SSA could be driven to a large extent by VRE, but only if investments in VRE can be effectively de-risked, if due attention is given to grid reinforcement and expansion, and if demand can be driven to grow in line with supply. However, while there is consensus that global decarbonization efforts will require end-use electrification eventually (Eurelectric 2018), the bulk of energy demand across SSA, especially outside of South Africa, currently still comes from the non-electrified sectors. These sectors include household cooking fuels, typically traditional uses of biomass (IEA 2022a), diesel and other fuels for road and other transportation, and solid fuels used for direct combustion in high-temperature processes in industry, although the industrial base in most SSA countries is small.

Electrification cannot happen overnight, and there is an unavoidable near- and medium-term role for fossil fuels in cooking, transportation, and industry across SSA. It is unrealistic to expect rapid electrification of the vehicle fleet, or a sudden wholesale shift from biomass-based to electric cooking, given the necessary scale of grid reinforcement and buildout. Let us look at the non-electrified sectors one by one to identify the opportunities and challenges.

Cooking: Liquid petroleum gas (LPG) is generally considered a realistic—though by no means easy (Hollada et al. 2017)—near-term alternative to traditional biomass. LPG is widely seen as a less costly option than electrifying cooking in the short term, but it offers similar health benefits in terms of reducing indoor air pollution (IEA 2022a). LPG can be derived either from oil or gas, so there is likely to be an increase in fossil fuel-related emissions from the household sector in SSA as demand continues to grow, until electrification can displace LPG use.

Passenger and freight transportation: The current vehicle fleet across SSA consists mostly of secondhand vehicles exported from Global North countries (UNEP 2020). The Global North continues its drive toward transportation fleet electrification, and many countries and car manufacturing companies plan to stop the domestic sale of internal combustion engine vehicles by 2040. It is likely that SSA will renew its vehicle fleets largely via the import of internal combustion cars currently still on the road in the Global North.
Therefore, vehicle fleet electrification in SSA is likely to lag somewhat behind electrification of transportation fleets in the Global North. With increasing demand for transportation, the demand for oil products in the transportation sector will thus continue to rise in the near term (Gorham 2022). Electrification of heavy freight transportation is likely to take even longer than for personal cars. Conversely, for two- and three-wheelers, the trends are expected to play out more quickly. For many people across Africa, their first exposure to electric mobility may happen through electric motorbikes and tuktuks.

Cement making: Cement making is the largest GHG emitter in SSA's heavy industry sector and supports countries' growing demand for construction (McKinsey 2021). We theorize that the main feasible long-term option for full decarbonization is the use of carbon capture and storage. This is because the process emissions from clinker production cannot easily be phased out, although substantial research and piloting on other forms of low-carbon cement through material substitution may yield promising results in the future (Sterl et al. 2017). In any case, fossil fuels (mostly natural gas and coal) are likely to continue to be used as a direct heat source for SSA's growing cement industry for the foreseeable future.

Steelmaking: Unlike cement, steel is an internationally traded commodity, and any strong growth in steelmaking in SSA is likely to be driven by a small set of global players dominating the steel industry who have largely already committed to decarbonizing steel production. Steelmaking in SSA currently relies mainly on electrified recycling of scrap metal (World Steel Association 2021), but in the future, if a primary steelmaking sector were to burgeon across SSA, it would probably adopt the direct reduction of iron method, which could use green hydrogen as a combustion fuel instead of natural gas (Kinch 2022).

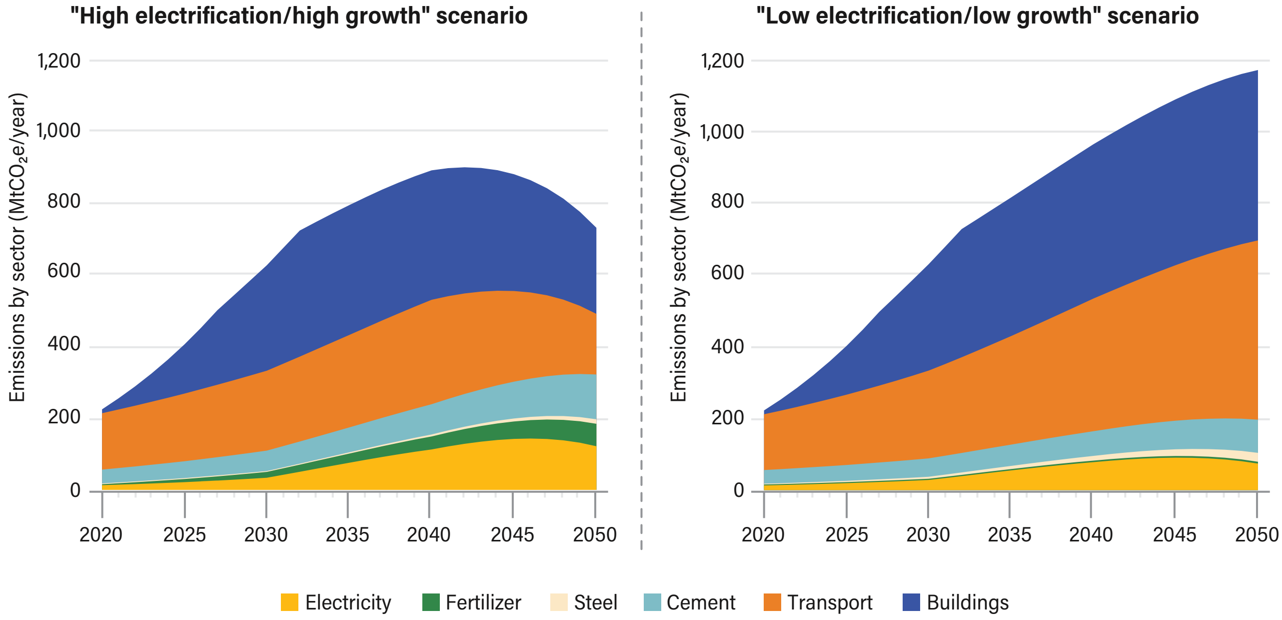
Nitrogen fertilizer production: The main feasible route for long-term decarbonization appears to be using green hydrogen. However, in the near term, the prevailing use of natural gas is expected to grow. Current production of fertilizer per capita in SSA is extremely low by international standards (1.5 kg fertilizer per capita), as is consumption of fertilizer per hectare of arable land (23 kg per hectare, compared to 157 kg in the EU and 383 kg in China) (World Bank 2022a; 2022b; 2022c). Even at these low levels, up to 80 percent of fertilizer across SSA is currently imported.

A key question is how high the demand for fossil fuels, in particular oil and gas, could rise in buildings, transportation, and industry in both the short and long term. To answer this, we elaborated two illustrative scenarios for energy use and emissions across SSA, one reflecting relatively fast technological and economic progress across SSA and another reflecting slower changes. The results in terms of annual sectoral emissions from SSA countries (excluding South Africa) are shown in Figure 4. It appears that, no matter the pathway, the order of magnitude of African oil and gas demand is likely to remain a small fraction of world demand. Note that this analysis focuses on prospects for demand growth and does not answer how this demand could be met (e.g., whether domestically or through imports) and which would carry lower risks. See the Appendix for a summary of how these scenarios were developed.

These scenarios help us understand the potential range of fossil fuel need or use in African countries. The projections suggest that while domestic demand for oil and gas for nonpower uses in SSA may initially grow substantially, total demand for oil could fall in the 2040s if electrification and a shift toward hydrogen in nascent steel and

FIGURE 4

Illustrative scenarios for sectoral emissions from modern forms of energy and industry until 2050 in sub-Saharan Africa, excluding South Africa



Notes: Emissions from traditional use of biomass are not counted. This explains the kink in the graph around 2030, when traditional biomass for cooking is assumed to become fully phased out (see Appendix). Post-2030, emissions from cooking increase at a slower pace as the share of fossil fuels in the cooking mix stops rising along with the demand for energy for cooking.

Source: Developed by the authors using the Climate Action Tracker's PROSPECTS tool (NewClimate Institute 2021).

fertilizer industries make important strides until that time. Outside of the cement sector, gas demand growth may peak in the 2040s as consequence of alternative fuels and electrification taking hold. Overall CO_2 emissions from these sectors would only reach between 0.4 and 0.6 tCO_2e/capita by 2050 (having already peaked by then), which is still far below the world average.

An overall picture emerges that demand for oil and gas products in SSA may reach their maximum around the 2040–50 decade if substantial progress is made on modern technology diffusion, without resulting in dangerous emissions increases on a global level and while allowing SSA countries to grow an industrial base beyond cement production.

However, the precise role of oil and gas on a country-by-country level needs to be elaborated through further research, as each country has a unique starting point and situation, in terms of available resources (e.g., whether a country is importing fossil fuels or has sufficient domestic resources) and the specific outlook for different industries in each country. Scientific literature on specific countries' industrialization pathways is particularly scarce, even on a continent-wide scale: Out of the 54 published academic articles researching fully decarbonized energy systems for Africa or African countries, only 15 investigated energy sectors other than the power sector, and most of these focused on transportation. Industry was the least-covered sector with only two articles (Oyewo et al. 2023). While some countries have industrialization plans, such as the Ethiopia Industrial Development Strategic Plan (Federal Ministry of Industry 2013), there is thus a general lack of research on what these plans would mean for fossil fuel demands and how they could be harmonized with objectives on electrification.

GIVEN CURRENT AND FUTURE INTERNATIONAL MARKET SIGNALS, WHAT ARE THE OPPORTUNITIES AND RISKS IN ENERGY EXPORTS FROM SUB-SAHARAN AFRICA?

It is expected that the focus of oil and gas exploration on the African continent will increasingly shift toward meeting domestic demand rather than exports, as larger sections of SSA's population gain access to modern forms of cooking and transportation and nascent industry develops (IEA 2022a; McKinsey 2022) (cf. the previous section). However, there will continue to be a role for oil and gas exports in the coming decades (AEC 2020). Several African countries still see oil and gas exports as a major economic opportunity; but given the context of global decarbonization, countries will need to assess the opportunities, costs, and risks involved. Further oil and gas development may lead to stranded assets that no longer produce government income, and countries could miss out on other high-potential export sectors (Climate Action Tracker 2022).

What are the risk considerations for fossil fuel investment predominantly for export markets in sub-Saharan Africa?

Debates around African countries' ongoing efforts to expand oil and gas exploration sometimes frame their legitimate desires to earn foreign revenues as fully unaligned with the global efforts to achieve decarbonization (Africanews 2022)—in essence, pitting climate change concerns against equity concerns. However, this reductionist argument glosses over much-needed nuance. What if the exploration of a limited amount of oil and gas would allow those African countries to earn the revenue needed to finance clean energy growth (or other desirable development projects) domestically (Davis et al. 2021)? Could the gains of domestic clean energy growth outweigh the negative environmental consequences of a limited expansion of oil and gas exploration? After all, Norway—often lauded nowadays as a leader in various areas of decarbonization, with a near 100 percent renewable electricity supply and the world's highest penetration of electric vehicles—also gained its historical wealth through oil exports (Feingold 2022).

Given Africa's historically relatively limited contribution to global oil and gas production (Climate Action Tracker 2022), we argue here that its relatively low share in unexplored oil and gas reserves and its limited domestic consumption are unlikely to "break the carbon budget" before any other countries. The main question around developing new infrastructure for oil and gas exports from Africa is therefore not so much "Is this in line with climate goals?" but, rather, "Who owns the financial risks linked to such assets in a decarbonizing world?" (Mulugetta et al. 2022).

International organizations like the IEA and IRENA have argued that global consumption of oil and gas needs to start falling soon and undergo drastic reductions by mid-century to limit global warming. The IEA has also argued that remaining in line with net-zero objectives will require a stop on any development of new oil and gas fields (IEA n.d.), and several major financial institutions, such as HSBC Bank, have aligned themselves with these targets (HSBC 2022). Other global dynamics play critical roles in influencing current positions, such as Russia's illegal invasion of Ukraine in early 2022. While the disappearance of natural gas exports from Russia to Europe was assumed by some to create an opportunity for increased African gas exports to Europe (Pelz 2022), in practice Europe has accelerated progress toward electrification, which could well lead to a medium-term drop in European gas demand rather than a rise (Goldthau and Tagliapietra 2022). At the global level, however, the many proposed investments in oil and gas projects that are still under consideration demonstrate that the oil and gas industry is still far from aligning itself with the Paris Agreement's long-term goals (Carbon Tracker 2022). These mixed market signals are causing substantial uncertainty about the medium-term viability of new oil and gas infrastructure investments in Africa.

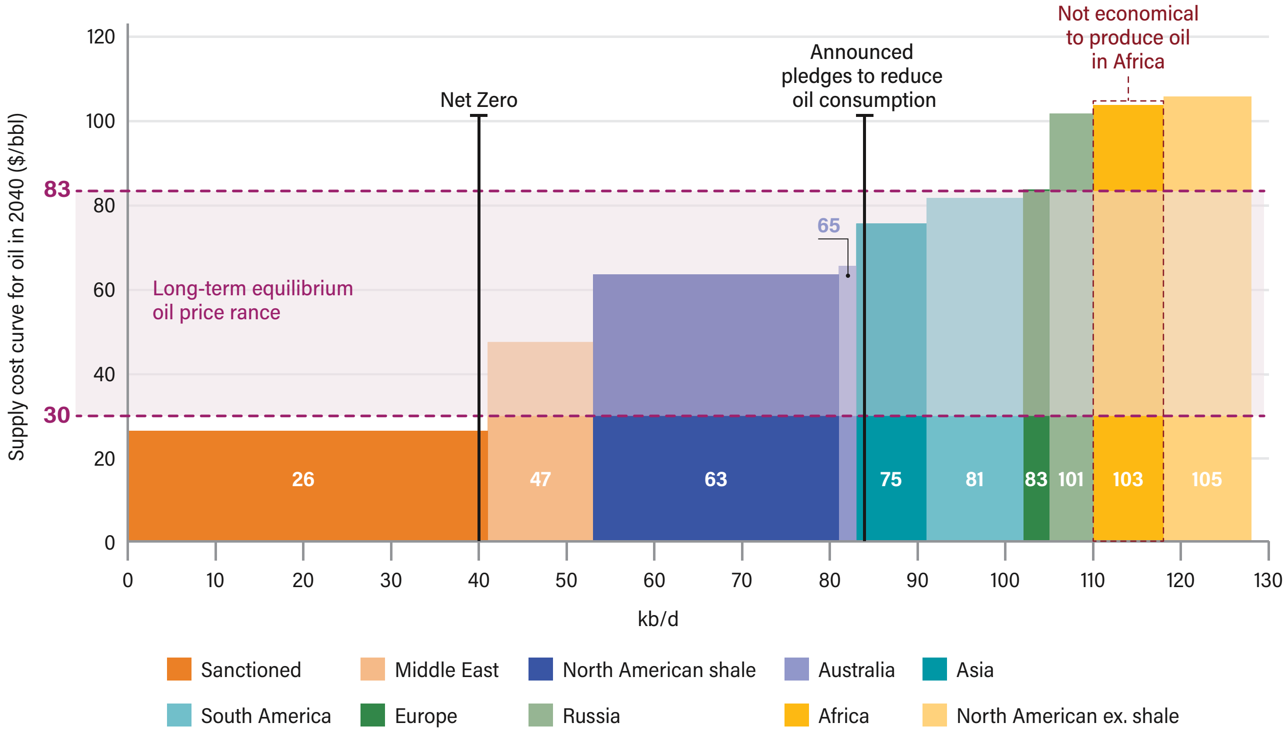
Whatever the uncertainties in the short term, it is likely that by 2040 global oil and gas demand will be substantially below current levels, even if domestic demand in SSA rises until then. The danger for states or national oil and gas companies in investing in new extraction infrastructure for export therefore lies in potentially being left with stranded assets which do not generate government income (Semieniuk et al. 2022)—given that global supply will tend to be met by the least-cost suppliers and given that these suppliers tend not to be located in Africa but in the Middle East (Figure 5) (Rystad Energy 2019).

While domestic demand in SSA for oil and gas and their derivatives will rise in the short to medium term, this will not prevent the global demand curve from dropping, so the risk that African supply may not be the least-cost option will continue to be present.

The picture painted by recent experience is not the rosiest. Among the many SSA countries that announced commercially exploitable oil and gas discoveries in recent years, the three that managed to reach production by 2020 (Mauritania, Ghana, and Niger) earned substantially lower revenues than initially forecast, largely due to production values remaining far below initially optimistic projections. In the case of Mauritania, revenues were as much as 90 percent lower than forecast (Mihalyi and Scurfield 2020). Further, oil and gas discoveries announced by several countries, including Sierra Leone and Liberia, turned out not to be commercially viable (Mihalyi and Scurfield 2020).

FIGURE 5

Marginal supply cost curve for existing and future oil exploration projects worldwide



Notes: Figure 5 shows how the potential production (in million barrels per day) compares to the expected global demand under different scenarios of global oil demand development by 2040. Sanctioned projects refer to projects that are either operational or for which final investment decisions have been made.

Source: Data from Rystad Energy (2019).

In response to these uncertainties, SSA countries with oil and gas resources will therefore need to balance short- to medium-term opportunities with the long-term risks and opportunity costs. The risks are most acute in circumstances where it would take many years to bring fossil resources into production, given the volatility of commodity price markets and the time needed to develop alternative economic activities.

What are the continent's future opportunities in green hydrogen and minerals?

How do these industries compare in terms of revenue-earning potential and local economy benefit?

With the long-term prospects for oil and gas as revenue-generating commodities declining, countries in SSA may look at other options instead of, or alongside, exploiting fossil fuel resources for export. Some countries could conceivably earn export revenues from resources essential to global decarbonization—for instance, from green hydrogen and critical minerals.

Green hydrogen and derived products

Given widespread availability of high-quality resources for renewable electricity generation in close proximity to coastlines (Sterl et al. 2022), the IEA estimates that Africa could produce up to 5,000 Mt of green hydrogen per year at the competitive cost of less than $2/kg within 200 km of the coast (IEA 2022a). Recent IRENA analysis integrated the option of building electrolyzers to produce cheap green hydrogen from VRE plants into cost-optimization models for capacity expansion in North Africa. The analysis found that this region could produce up to 24 Mt of H_2 per year by 2040 at a cost of \$2/kgH_2 or less (IRENA 2023a). Green hydrogen and hydrogen-derived products (such as ammonia) could find important uses in decarbonizing heavy industry such as steelmaking, as well as in fertilizer production. However, the IEA also forecasts only a slow takeoff of green hydrogen demand worldwide. This, combined with the high transportation costs of shipping hydrogen in pure form and the limited current development within SSA of potential major industrial users of green hydrogen (e.g., fertilizer, chemicals, and steel industries), may mean that hydrogen would only compete with oil and gas as a prime export opportunity by the 2030s.

By 2050, however, global hydrogen demand could potentially reach up to 800 Mt/year (ETC 2021b), meaning that low-cost hydrogen from Africa could be well-positioned to compete in the global market. If Africa were to produce 50 Mt of this hydrogen, and if prices of $1,500–$2,000/t were to prevail, this would provide $100 billion/year in revenue, similar to Nigeria's annual revenue from oil and gas over the last decade (NEITI 2022).

In the vast majority of cases, the economic route for hydrogen production for export is likely to involve producing derivatives like ammonia, which—unlike pure hydrogen—could be feasibly transported (Liebreich 2022). However, the opposite route—bringing the industry to African countries instead of exporting African hydrogen derivatives to Europe or elsewhere—should be considered too. For instance, major potential changes in the optimal design of global iron and steel sector value chains may also make it possible for African countries like Guinea with iron ore resources (USGS 2022) to become locations for hydrogen-based sponge iron production, exporting the iron to steelmakers in developed countries.

In practice, there may be large economic risks linked to some proposed projects. Consider the suggested 30 GW AMAN power-to-hydrogen plant in Mauritania, which would cost $40 billion (IRENA 2023a)—an investment volume roughly six times Mauritania's entire annual GDP. The dangers of "Dutch Disease" economic consequences, whereby dominance of one sector inhibits development of others, cannot be ruled out (Asiamah et al. 2022). The question of who will share in the benefits and risks of green hydrogen megaprojects must also be investigated. Historically, in the absence of strong institutions, large-scale export-based projects have not always led to widely shared prosperity, either in SSA or elsewhere (Davis et al. 2021).

Viewing Africa simplistically as the "world's hydrogen hotspot" must be avoided by moving to country-level narratives that consider each nation's capabilities and opportunities—especially as substantial investment and offtake agreements would be required to get this market off the ground, and its economic promise is not at all certain.

Critical minerals

The African continent is already a major source of some of the minerals required for electrification and the decarbonization of electricity systems. For instance, Africa's share in global production of cobalt, manganese, and natural graphite (needed for batteries) exceeded 30 percent in 2020, and it is estimated that large deposits of other minerals, like as nickel, which are needed in the energy transition, exist across the continent (IEA 2022a). Global demand for these minerals is expected to grow substantially as energy transitions progress, and the IEA estimates that if Africa were to keep its current market share in minerals for batteries until 2050, total export revenues could equal the revenue from fossil fuel exports by then (IEA 2022a). Importantly, green mineral deposits tend to be distributed very unevenly by country. For instance, nearly 100 percent of Africa's cobalt production currently comes from the Democratic Republic of Congo (IEA 2022a).

While exporting critical minerals appears to be a promising opportunity on paper, planning to build up and maintain the sector needs to be done with care. The supply of certain materials like lithium may undergo bottlenecks in the future (Greim et al. 2020), and materials that are in demand at present may be replaced by better alternatives in the future (Gielen 2021). Global trade in such minerals will therefore not be immune to price shocks similar to those currently experienced by the global gas market, or to similar risks of stranded assets (given the long lead time of new mines). If countries opt for the route of minerals exploration, implementation of proper resource governance will be essential to ensure that the minerals value chain adds substantial value to the local economy in the form of job creation, innovation, and export of the processed products (e.g., battery production in Zambia and the Democratic Republic of Congo [UNECA 2022]) and that mining is done sustainably, avoiding negative consequences for human rights and for the environment.

Synthesis

Opportunities exist for commodity exports aligned with global decarbonization efforts that appear highly promising on paper for many SSA countries and that may have better long-term prospects than oil and gas exploration.

However, the global markets for these commodities are not yet mature, and it is no surprise that policymakers across SSA may be reluctant to forgo investments in new oil and gas infrastructure, which promises more immediate returns.

Once again, a country-specific investigation of opportunities and risks will help countries make concrete plans for resource utilization in line with their potential. In this context, generalized "African countries should export green hydrogen or minerals and forgo oil and gas altogether" tropes are unhelpful.

CONCLUSION

Our synthesis presents the chief critical questions in determining African energy transition pathways, along with the best available data that currently address these questions. The evidence base for many of these issues is currently very thin, and divergences and blind spots abound (Figure 6). Nevertheless, we arrive at the following conclusions:

- In principle, SSA countries could build cost-effective electricity systems based primarily on VRE. This will only be possible if reductions in the cost of capital for VRE can be achieved through de-risking, large financial flows can be mobilized, and existing grids are strengthened and expanded to absorb more VRE. Existing models often underemphasize these important variables and how they differ from one country to another. Some countries already achieve sufficiently low cost-of-capital values to make VRE a cost-effective option compared to fossil fuels, whereas others lag behind (Figure 2). Some countries attract more finance than others. And some countries' grids are much more capable of absorbing high shares of VRE than other countries' grids. High-resolution network-level studies are needed at the country level to model the feasibility of running electricity systems at high VRE penetration.
- Electricity demand growth in SSA is constrained as much by per capita income as by supply (with grid expansion to low-bill customers often not commercially viable). Even with successful access strategies, SSA per capita electricity demand will still be substantially below middle-income levels by 2030. Strategies are needed to break the vicious cycle of low grid reliability pushing C&I customers toward on-site generation, leading to lower utility revenue.
- Across the household, transportation, and industrial sectors in Africa, growing economic development will likely require increases in fossil fuel use in the near term to meet increased demand for cooking, mobility, housing, and production. While electrification-plus-renewables is a long-term option in many of these sectors, such processes will take time. The near-term practical limits of clean alternatives in cooking, cement-making, and transportation should be acknowledged. LPG will likely play a key role in moving to cleaner cooking; gas will continue to be used in cement production; and road transportation will rely on diesel and gasoline for longer than in high-income countries. New technologies, notably green hydrogen, that may offset the need for fossil fuels in industrial sectors such as steel and fertilizer, warrant deeper investigation. The viability of defossilization options will vary sector by sector and country by country, emphasizing that sector- and country-level analysis is urgently needed.
- Some SSA countries could gain valuable export revenues from oil and gas resources. But there are risks that future exports of oil and gas from countries in Africa may be threatened by the pace of decarbonization in developed economies, with available data pointing to high risks of low-return assets, despite the rising near- and medium-term trend in demand for oil and gas within SSA itself. The export opportunity from green hydrogen and the minerals required to achieve global decarbonization may provide alternatives to earn export revenue. International trends suggest that revenue generation streams from green hydrogen and green minerals expansion may be attractive for the continent, warranting country-specific scenario analyses.

The four critical questions that we posed at the beginning of this brief (Figure 1) therefore point to a need for additional analysis that needs to be undertaken specifically at the country level if it is to inform energy policymaking across SSA. We summarize the blind spots and the additional analysis needed in Figure 6. The "ifs" and "thens" of the earlier points are thus complemented by clear "hows": The existing research base needs to be expanded with specific analyses to complete the picture of what is needed for each African country to chart its energy future in a sustainable way.

FIGURE 6

Key questions, divergences, and blind spots in current projections and scenarios and the additional analysis needed to close the modeling and analysis gap

KEY QUESTION	DIVERGENCE AND BLIND SPOTS	ADDITIONAL ANALYSIS NEEDS
Are VRE sources truly the cost-effective option for power in sub-Saharan Africa?	▪ The cost of capital for each technology and by each country ▪ The availability of mobilizable capital across technologies ▪ Role of gas for power generation, either as base load or for flexibility ▪ Cost of total system buildout (generation, T&D, storage, etc.)	▪ Country-specific analysis of the true cost of technology given country finances ▪ Country-specific mechanisms to improve affordability when cost of capital is high ▪ Country-specific cost-optimal solution for power generation, T&D, and storage ▪ Grid reinforcement needs to enable high-VRE systems
How fast could electricity demand grow across sub-Saharan Africa, given prospects for income growth in both the short and long terms?	▪ Electricity demand projections vary widely across studies and scenarios ▪ Explicit consideration of trade-offs between grid expansion and off-grid access not always included in studies	▪ Extent to which off-grid connections should be used to provide energy access ▪ Demand projections that reflect price elasticity, purchasing power, and suppressed demand ▪ Effect of choice for grid expansion or off-grid buildout on business models for power generation
What roles will oil and gas play in cooking, transportation, and industry in the short and long term in sub-Saharan Africa?	▪ Extent and speed to which domestic industries, households, and transportation electrify	▪ Forecasts for larger vehicles (buses, trucks) supply and ability to "go green" ▪ Sub-Saharan Africa-specific analysis of decarbonization of hard-to-abate sectors ▪ Accurate techno-economic parameters for African industry (also by country)
What are emerging export opportunities in green hydrogen, green minerals, and fossil fuels in sub-Saharan Africa, and what are the associated risks?	▪ Risks for SSA to capitalize on natural gas & mineral resources to meet international demand ▪ Realism of Africa becoming hub for hydrogen production for domestic purposes and export	▪ Detailed modeling on how country revenues and economic needs affect energy transition pathway choices

Source: Authors.

APPENDIX: SECTORAL FOSSIL FUEL DEMAND AND EMISSION PROJECTIONS IN SUB-SAHARAN AFRICA

This appendix describes the assumptions used in the calculations toward the sectoral emissions projections for SSA countries shown in Figure 4. These assumptions are the authors' own and purely serve illustrative purposes to show possible developments of energy demand and emissions across sub-Saharan Africa, excluding South Africa. They are not meant to necessarily be aligned with comparable assumptions from other organizations and should not be interpreted as reflecting the authors' opinion on what would or could be the most realistic pathways, only to show a range of possibilities covering low-ambition to high-ambition options.

In **cooking**, we assume increases in socioeconomic development and a corresponding more intensive use of energy at the household level to lead to a 5 percent energy demand growth per year,[2] alongside a full phase-out of traditional biomass in favour of cleaner LPG by 2030 (which is seen to be a less costly option than electrifying cooking on the short term, but offering similar health benefits), followed by a drive toward 75 percent electrification by 2050 in the high scenario, and toward 50 percent electrification in the low scenario. This would lead to a final LPG consumption of roughly 60–120 Mt/year by 2050, roughly the equivalent of 2.5 Mmboe/day. Under the high electrification scenario, this demand is already past its peak come 2050. For comparison, *current* global oil demand lies around 100 Mmboe/day (IEA 2022e).

In **passenger transportation**, we assume demand (in passenger-kilometers) to grow at an average of 5 percent per year,[3] with passenger cars and buses transitioning to 100 percent electric by 2050 in the high scenario and to 50 percent electric in the low scenario. In **freight transportation**, sectoral growth rates (in tonne-kilometers) are assumed to be identical, but the transportation fleet only starts transitioning to electric in 2035, reaching 50 percent electric truck penetration under the high scenario and 10 percent under the low scenario. Overall, final oil consumption in transportation lies between roughly 0.8 and 2.5 Mmboe/day by 2050 and, under the high electrification scenario, has already peaked by then.

In **cement making**, we assume that the main feasible long-term option for full decarbonization is the use of carbon capture and storage, given that the process emissions from clinker production cannot easily be phased out from the process. Therefore, natural gas will continue to be used as a direct heat source. We assume cement production to grow at 4 percent per year under the high scenario, roughly reflecting future GDP growth assumptions (IEA 2022a), and at population growth rates under the low scenario, which would mean constant cement production per capita. The final natural gas consumption here grows to 11–18 bcm/year by 2050. For comparison, *current* global natural gas demand lies at around 4,000 bcm/year (IEA 2022d).

In **steelmaking**, on the other hand, we assume production processes to shift away from the currently prevalent recycling of scrap metal (World Steel Association 2021) to primary steelmaking using the direct reduction of iron route, reaching an annual production of 50 kg steel per capita, and initially using natural gas as a heat source but shifting to green hydrogen over time. Under the high scenario, hydrogen use already reaches 80 percent by 2030; under the low scenario, it reaches 60 percent by 2050. In both scenarios, given the strong growth of the sector from a very low base, final consumption of natural gas increases substantially until 2050, reaching 4.7 (low) to 9.5 (high) bcm/year.

In **nitrogen fertilizer production**, we assume the consumption of fertilizer to grow up to the same levels per hectare of cropland as in India today in the high scenario and to grow in line with population growth in the low scenario (i.e., unchanged demand of fertilizer per capita). In the high scenario case, assume that domestic production rises up to 60 percent of total consumption, again reflecting India's level today, whereas in the low scenario, the domestic share stays flat at approximately 30 percent. In both cases, we assume that green hydrogen will gradually take over from natural gas (20 percent by 2030 to over 80 percent by 2040). This results in a strong ramp-up of gas consumption until 2035 before tapering off to almost zero by 2050.

While these scenarios for steelmaking and fertilizer may appear ambitious, we note that given the large amount of capital needed to finance steel and fertilizer plants, investments for these will most likely come from international companies that have already made global net-zero commitments and that will therefore want to build plants in line with those commitments (The Climate Group 2022).

Lastly, the different developments of electrification and technology choice in end-use sectors have an impact on **electricity demand**. We estimate electricity demand to grow to somewhere in the range of 1.2–1.9 MWh/year/capita by 2050 under the low and high electrification assumptions, representing roughly today's levels in India and Costa Rica, respectively. We hypothesize the power mix to shift rapidly to a higher penetration of VRE, reaching 80 percent by 2050, initially at the expense of hydropower but, starting as of 2030, also of natural gas, diesel, and other heavy fuels. This leads to an expected peak in final natural gas consumption for power generation of roughly 25–50 bcm/year around 2040.

ENDNOTES

1. Note that these numbers mix household and industrial or commercial consumption. It is to be understood that household consumption levels would typically be even much lower.
2. Composed of an assumed 2 percent growth in energy use per square meter and a 1 percent growth in floor space per capita, with a population growth rate of about 2 percent per year over the period 2020–2050.
3. Composed of an assumed 3 percent increase in per-capita demand at an average population growth of 2 percent.

REFERENCES

AEC (Africa Energy Chamber). 2020. "Africa Energy Outlook 2021." https://energychamber.org/report/africa-energy-outlook-2021. Accessed November 7, 2022.

AFC (Africa Finance Corporation). 2022. *Roadmap to Africa's COP: A Pragmatic Path to Net Zero*. https://s3.eu-central-1.amazonaws.com/afc-assets/afc/11378_AFC_COP_White_paper_V2_LR-1.pdf.

African Union. 2021. "African Union Launches World's Largest Single Electricity Market (AFSEM)." https://au.int/en/pressreleases/20210604/african-union-launches-worlds-largest-single-electricity-market-afsem.

African Union Commission. 2021. "Is Energy Transition the Answer to Africa's Climate Change and Socio-Economic Development? What Will It Take for Africa to Reach Net-Zero Emissions?" https://au.int/en/pressreleases/20211109/energy-transition-answer-africas-climate-change-and-socio-economic.

Africanews. 2022. "Climate Activists Call on Countries to Stop Funding New Gas Projects in Africa." https://www.africanews.com/2022/11/15/climate-activists-call-on-countries-to-stop-funding-new-gas-projects-in-africa/.

Agutu, Churchill, Florian Egli, Nathaniel J. Williams, Tobias S. Schmidt, and Bjarne Steffen. 2022. "Accounting for Finance in Electrification Models for Sub-Saharan Africa." *Nature Energy* 7 (7): 631–41. https://doi.org/10.1038/s41560-022-01041-6.

Alova, Galina, Philipp A. Trotter, and Alex Money. 2021. "A Machine-Learning Approach to Predicting Africa's Electricity Mix Based on Planned Power Plants and Their Chances of Success." *Nature Energy* 6 (2): 158–66. https://doi.org/10.1038/s41560-020-00755-9.

Al-Zu'bi, Maha, Sintayehu W. Dejene, Jean Hounkpè, Olga Laiza Kupika, Shuaib Lwasa, Mary Mbenge, Caroline Mwongera, et al. 2022. "African Perspectives on Climate Change Research." *Nature Climate Change*, November 2022. https://doi.org/10.1038/s41558-022-01519-x.

Anvane-Obame, Judicaël Léonce Eugène, Alexis-Léandre Okouma, Prisca Ngoloa, Guy Léonce Ondo Makounga, and Arnold Stéphane Kapitho. 2019. *Analyse de l'Offre Énergétique du Gabon à l'Horizon 2045 et Évaluation des Émissions de* CO_2. Libreville, Gabon: Ministère de l'Énergie et des Ressources Hydrauliques & Agence Internationale de l'Énergie Atomique.

Asiamah, Oliver, Samuel Kwaku Agyei, Bossman Ahmed, and Ellen Animah Agyei. 2022. "Natural Resource Dependence and the Dutch Disease: Evidence from Sub-Saharan Africa." *Resources Policy* 79 (December): 103042. https://doi.org/10.1016/j.resourpol.2022.103042.

Balabanyan, Ani, Yadviga Semikolenova, Arun Singh, and Min A. Lee. 2021. *Utility Performance and Behavior in Africa Today—Summary Report*. https://openknowledge.worldbank.org/bitstream/handle/10986/36178/Summary-Report.pdf?sequence=1&isAllowed=y. Accessed November 7, 2022.

Barasa, Maulidi, Dmitrii Bogdanov, Ayobami Solomon Oyewo, and Christian Breyer. 2018. "A Cost Optimal Resolution for Sub-Saharan Africa Powered by 100% Renewables in 2030." *Renewable and Sustainable Energy Reviews* 92 (September): 440–57. https://doi.org/10.1016/j.rser.2018.04.110.

BNEF (Bloomberg New Energy Finance). 2022. "Cost of New Renewables Temporarily Rises as Inflation Starts to Bite." Blog. June 30. https://about.bnef.com/blog/cost-of-new-renewables-temporarily-rises-as-inflation-starts-to-bite/.

Bogdanov, Dmitrii, Javier Farfan, Kristina Sadovskaia, Arman Aghahosseini, Michael Child, Ashish Gulagi, Ayobami Solomon Oyewo, et al. 2019. "Radical Transformation Pathway toward Sustainable Electricity via Evolutionary Steps." *Nature Communications* 10 (1): 1077. https://doi.org/10.1038/s41467-019-08855-1.

Breyer, C., S. Khalili, D. Bogdanov, M. Ram, A.S. Oyewo, A. Aghahosseini, A. Gulagi, et al. 2022. "On the History and Future of 100% Renewable Energy Systems Research." *IEEE Access* 10: 78176–218. https://doi.org/10.1109/ACCESS.2022.3193402.

Carbon Tracker. 2022. "Paris Maligned: Why Investors Should Assess the Climate Alignment of Oil & Gas Companies." https://carbontracker.org/wp-content/uploads/2022/12/Paris-Maligned.pdf.

Chen, A.A., A.J. Stephens, R. Koon Koon, M. Ashtine, and K. Mohammed-Koon Koon. 2020. "Pathways to Climate Change Mitigation and Stable Energy by 100% Renewable for a Small Island: Jamaica as an Example." *Renewable and Sustainable Energy Reviews* 121 (April): 109671. https://doi.org/10.1016/j.rser.2019.109671.

Climate Action Tracker. 2022. "Natural Gas in Africa: Why Fossil Fuels Cannot Sustainably Meet the Continent's Growing Energy Demand." https://climateactiontracker.org/documents/1048/CAT_2022-05_Report_NaturalGasinAfrica.pdf.

The Climate Group. 2022. "Major Businesses Commit to 100% Net Zero Steel." https://www.theclimategroup.org/our-work/press/major-businesses-commit-100-net-zero-steel. Accessed November 7, 2022.

Davis, William, Andrew Bauer, and Papa Daouda Diene. 2021. *Managing Senegal's Oil and Gas Revenues*. Natural Resource Governance Institute. https://resourcegovernance.org/sites/default/files/documents/managing_senegals_oil_and_gas_revenues.pdf.

DWF Group. 2018. "Will Africa Leapfrog Traditional Energy Infrastructure and Head Straight for Off-Grid Renewables?" https://dwfgroup.com/en/news-and-insights/insights/2018/4/will-africa-leapfrog-traditional-energy-infrastructure-and-head-straight-for-off-grid-renewables.

The Economic Times India. 2022. "G7 Vows to End Fossil-Fuel Financing Abroad by End 2022: Statement," May 27, 2022. https://economictimes.indiatimes.com/industry/renewables/g7-vows-to-end-fossil-fuel-financing-abroad-by-end-2022-statement/articleshow/91835949.cms.

The Economist. 2017. "Africa Might Leapfrog Straight to Cheap Renewable Electricity and Minigrids." https://www.economist.com/special-report/2017/11/10/africa-might-leapfrog-straight-to-cheap-renewable-electricity-and-minigrids.

EEA (European Environment Agency). 2017. "Energy in Europe—State of Play." https://www.eea.europa.eu/signals/signals-2017/articles/energy-in-europe-2014-state-1. Accessed November 7, 2022.

Egli, Florian, Bjarne Steffen, and Tobias S. Schmidt. 2019. "Bias in Energy System Models with Uniform Cost of Capital Assumption." *Nature Communications* 10 (1): 4588. https://doi.org/10.1038/s41467-019-12468-z.

EIA (U.S. Energy Information Administration). 2022. "2021 Total Electric Industry—Customers." https://www.eia.gov/electricity/sales_revenue_price/pdf/table1.pdf.

Enel Green Power. 2018. *Africa: The Land of Renewables*. https://www.enelgreenpower.com/stories/articles/2018/06/africa-the-land-of-renewables.

ESI Africa. 2022. *Exploration into the Role of T&D in Africa's Low Energy Access Rates*. https://www.esi-africa.com/industry-sectors/transmission-and-distribution/exploration-into-the-role-of-td-in-africas-low-energy-access-rates/. Accessed November 7, 2022.

ESMAP (Energy Sector Management Assistance Program) and SE4All (Sustainable Energy for All). 2015. *Beyond Connections—Energy Access Redefined*. https://openknowledge.worldbank.org/bitstream/handle/10986/24368/Beyond0connect0d000technical0report.pdf?sequence=1&isAllowed=y. Accessed November 7, 2022.

ETC (Energy Transitions Commission). 2021a. *Making Clean Electrification Possible: 30 Years to Electrify the Global Economy*. https://www.energy-transitions.org/publications/making-clean-electricity-possible/#download-form. Accessed November 7, 2022.

ETC. 2021b. *Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy*. https://www.energy-transitions.org/wp-content/uploads/2021/04/ETC-Global-Hydrogen-Report.pdf.

EURactiv. 2022. "EU Aims to Make Africa a World Champion in Hydrogen Exports." https://www.euractiv.com/section/energy/news/eu-aims-to-make-africa-a-world-champion-in-hydrogen-exports/. Accessed November 7, 2022.

Eurelectric. 2018. *EU Electrification and Decarbonization Scenario Modelling*. https://cdn.eurelectric.org/media/3172/decarbonisation-pathways-electrificatino-part-study-results-h-AD171CCC.pdf.

European Commission. 2023. "New Reports Highlight 3rd Quarter Impact of Gas Supply Cuts." Directorate-General for Energy. https://energy.ec.europa.eu/news/new-reports-highlight-3rd-quarter-impact-gas-supply-cuts-2023-01-13_en.

Federal Ministry of Industry. 2013. *Ethiopian Industrial Development Strategic Plan (2013–2025)*. https://www.eebcouncil.org/images/publications/Ethiopian%20Industrial%20Development%20Strategic%20Plan%20(2013-2025).pdf.

Feingold, Spencer. 2022. "Norway's Massive Sovereign-Wealth Fund Sets Net-Zero Goals." https://www.weforum.org/agenda/2022/09/norways-massive-sovereign-wealth-fund-sets-net-zero-goal/. Accessed November 7, 2022.

Gielen, D. 2021. *Critical Materials for the Energy Transition*. https://irena.org/Technical-Papers/Critical-Materials-For-The-Energy-Transition. Accessed November 7, 2022.

Global Solar Atlas. 2020. *Solar PV Resource Availability*. 2020. https://globalsolaratlas.info. Accessed November 7, 2022.

Goldstone, Jack A. 2021. "The Battle for Earth's Climate Will Be Fought in Africa." https://diplomacy21-adelphi.wilsoncenter.org/article/battle-earths-climate-will-be-fought-africa. Accessed November 7, 2022.

Goldthau, Andreas, and Simone Tagliapietra. 2022. "Energy Crisis: Five Questions That Must Be Answered in 2023." https://www.nature.com/articles/d41586-022-04467-w. Accessed January 6, 2023.

Gorham, Roger. 2022. "To Decarbonize Transport, Help Developing Countries Deal with Junkers, Clunkers and Jalopies." World Bank Blog. June 23. https://blogs.worldbank.org/transport/decarbonize-transport-help-developing-countries-deal-junkers-clunkers-and-jalopies.

Greim, Peter, A.A. Solomon, and Christian Breyer. 2020. "Assessment of Lithium Criticality in the Global Energy Transition and Addressing Policy Gaps in Transportation." *Nature Communications* 11 (1): 4570. https://doi.org/10.1038/s41467-020-18402-y.

Gulagi, Ashish, Manish Ram, Dmitrii Bogdanov, Sandeep Sarin, Theophilus Nii Odai Mensah, and Christian Breyer. 2022. "The Role of Renewables for Rapid Transitioning of the Power Sector across States in India." *Nature Communications* 13 (1): 5499. https://doi.org/10.1038/s41467-022-33048-8.

HSBC. 2022. "HSBC Sets Net Zero Aligned Targets to Reduce Financed Emissions from Oil and Gas, Power and Utilities Sectors." https://www.hsbc.com/news-and-media/media-releases/2022/hsbc-sets-financed-emissions-targets-for-oil-and-gas-power-and-utilities. Accessed January 6, 2023.

Heptonstall, Philip J., and Robert J.K. Gross. 2021. "A Systematic Review of the Costs and Impacts of Integrating Variable Renewables into Power Grids." *Nature Energy* 6 (1): 72–83. https://doi.org/10.1038/s41560-020-00695-4.

Hollada, Jacqueline, Kendra N. Williams, Catherine H. Miele, David Danz, Steven A. Harvey, and William Checkley. 2017. "Perceptions of Improved Biomass and Liquefied Petroleum Gas Stoves in Puno, Peru: Implications for Promoting Sustained and Exclusive Adoption of Clean Cooking Technologies." *Int J Environ Res Public Health* 14 (2): 182. https://doi.org/10.3390/ijerph14020182.

IEA (International Energy Agency). 2020a. *Uruguay—Countries & Regions*. https://www.iea.org/countries/uruguay. Accessed November 7, 2022.

IEA. 2020b. *Climate Impacts on African Hydropower*. https://www.iea.org/reports/climate-impacts-on-african-hydropower. Accessed November 7, 2022.

IEA. 2020c. *Will System Integration of Renewables Be a Major Challenge by 2023*? https://www.iea.org/articles/will-system-integration-of-renewables-be-a-major-challenge-by-2023. Accessed November 7, 2022.

IEA. 2022a. *Africa Energy Outlook 2022*. https://iea.blob.core.windows.net/assets/6fa5a6c0-ca73-4a7f-a243-fb5e83ecfb94/AfricaEnergyOutlook2022.pdf.

IEA. 2022b. *SDG7 Data and Projections*. April 2022. https://www.iea.org/reports/sdg7-data-and-projections.

IEA. 2022c. "Global Energy Crisis Shows Urgency of Accelerating Investment in Cheaper and Cleaner Energy in Africa." https://www.iea.org/news/global-energy-crisis-shows-urgency-of-accelerating-investment-in-cheaper-and-cleaner-energy-in-africa. Accessed January 6, 2023.

IEA. 2022d. *Gas Market Report, Q3-2022*. https://iea.blob.core.windows.net/assets/c7e74868-30fd-440c-a616-488215894356/GasMarketReport%2CQ3-2022.pdf.

IEA. 2022e. *Oil Market Report—October 2022*. https://www.iea.org/reports/oil-market-report-october-2022. Accessed January 6, 2023.

IEA. n.d. *Net Zero by 2050—A Roadmap for the Global Energy Sector*. https://www.iea.org/reports/net-zero-by-2050. Accessed January 6, 2023.

IRENA (International Renewable Energy Agency). 2015. "From Baseload to Peak: Renewables Provide a Reliable Solution." Working Paper. Abu Dhabi: IRENA. http://www.irena.org/DocumentDownloads/Publications/IRENA_Baseload_to_Peak_2015.pdf.

IRENA. 2017. *Planning for the Renewable Future: Long-Term Modelling and Tools to Expand Variable Renewable Power in Emerging Economies*. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/IRENA_Planning_for_the_Renewable_Future_2017.pdf.

IRENA. 2018a. *Power System Flexibility for the Energy Transition. Part I: Overview for Policy Makers*. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Nov/IRENA_Power_system_flexibility_1_2018.pdf.

IRENA. 2018b. *Planning and Prospects for Renewable Power: West Africa*. https://www.irena.org/publications/2018/Nov/Planning-and-prospects-for-renewable-power. Accessed November 7, 2022.

IRENA. 2020. *Global Renewables Outlook: Energy Transformation 2050 (Edition 2020)*. Abu Dhabi: International Renewable Energy Agency. ISBN 978-92-9260-238-3.

IRENA. 2021a. *Soutien à la Révision des CDN—Rapport Final: Renforcement de Capacités en Modélisation Énergétique à Long Terme—Gabon*. https://www.irena.org/-/media/Irena/Files/Topics/Energy-Transition/Gabon_rapport_final_B046.pdf.

IRENA. 2021b. *Planning and Prospects for Renewable Power: Eastern and Southern Africa*. https://www.irena.org/publications/2021/Apr/Planning-and-prospects-for-renewable-power-Eastern-and-Southern-Africa.

IRENA. 2021c. *Feuille de Route pour le Sous-Secteur Électricité à l'horizon 2035—Niger*. https://www.irena.org/-/media/Irena/Files/Topics/Energy-Transition/20210714-Niger_feuille_de_route_lectricit_C056_updated.pdf.

IRENA. 2022a. *Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part I—Trade Outlook for 2050 and Way Forward*. https://www.irena.org/publications/2022/Jul/Global-Hydrogen-Trade-Outlook.

IRENA. 2022b. "Renewable Power Generation Costs in 2021." https://www.irena.org/publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021

IRENA. 2022c. *World Energy Transitions Outlook: 1.5°C Pathway*. https://irena.org/publications/2022/Mar/World-Energy-Transitions-Outlook-2022.

IRENA. 2023a. *Planning and Prospects for Renewable Power: North Africa*. Abu Dhabi: International Renewable Energy Agency.

IRENA. 2023b. *The Cost of Financing for Renewable Power.* https://www.irena.org/Publications/2023/May/The-cost-of-financing-for-renewable-power.

IRENA and State Grid Corporation of China. 2019. *Electrification with Renewables: Driving the Transformation of Energy Services*. https://www.irena.org/publications/2019/Jan/Electrification-with-Renewables.

Jacobson, Mark Z., and Mark A. Delucchi. 2018. "100% Clean, Renewable Energy Studies Provide Scientific Solution That Policymakers Can Rely On." *The Electricity Journal* 31 (2): 78–80. https://doi.org/10.1016/j.tej.2017.11.011.

Kenya Power. 2021. *Annual Report and Financial Statements—30th June 2021*. https://www.kplc.co.ke/img/full/KPLC%20Annual%20Report%20and%20Financial%20Statements%20for%20the%20year%20ended%2030.6.2021.pdf.

Kinch, Diana. 2022. "Direct-Reduced Iron Becomes Steel Decarbonization Winner." Blog. June 22. https://www.spglobal.com/commodityinsights/en/market-insights/blogs/metals/062222-dri-steel-decarbonization-direct-reduced-iron.

Koc, Cagan, Katarina Hoije, and Diederik Baazil. 2022. "Europe Optimal Market for Senegal's Gas, President Sall Says." https://www.bloomberg.com/news/articles/2022-09-08/europe-optimal-market-for-senegal-s-gas-president-sall-says.

Kuhudzai, Remeredzai Joseph. 2022. "President William Ruto Sworn In, Reaffirms Kenya's Commitment to Transition to 100% Clean Energy by 2030." https://cleantechnica.com/2022/09/13/president-william-ruto-sworn-in-reaffirms-kenyas-commitment-to-transition-to-100-clean-energy-by-2030. Accessed January 6, 2023.

Le Figaro. 2022. "Energies Fossiles : L'Afrique Est «Punie», Estime le Président du Niger." https://www.aljazeera.com/news/2022/6/15/africa-punished-by-investment-clamp-on-fossils-says-niger.

Lee, Jonathan T., and Duncan S. Callaway. 2018. "The Cost of Reliability in Decentralized Solar Power Systems in Sub-Saharan Africa." *Nature Energy* 3 (11): 960–68. https://doi.org/10.1038/s41560-018-0240-y.

Lee, Kenneth, Eric Brewer, Carson Christiano, Francis Meyo, Edward Miguel, Matthew Podolsky, Javier Rosa, and Catherine Wolfram. 2016. "Electrification for 'Under Grid' Households in Rural Kenya." *Development Engineering* 1 (June): 26–35. https://doi.org/10.1016/j.deveng.2015.12.001.

Liebreich, Michael. 2022. "The Unbearable Lightness of Hydrogen." Blog. December 12. https://about.bnef.com/blog/liebreich-the-unbearable-lightness-of-hydrogen/.

Lovins, Amory B. 2017. "Reliably Integrating Variable Renewables: Moving Grid Flexibility Resources from Models to Results." *The Electricity Journal* 30 (10): 58–63. https://doi.org/10.1016/j.tej.2017.11.006.

Lucas, Paul L., Anteneh G. Dagnachew, and Andries F. Hof. 2017. *Towards Universal Electricity Access in Sub-Saharan Africa—A Quantitative Analysis of Technology and Investment Requirements*. https://www.pbl.nl/sites/default/files/downloads/pbl-2017-towards-universal-electricity-access-in-sub-saharan-africa-1952_3.pdf.

McKinsey. 2021. *Africa's Green Manufacturing Crossroads: Choices for a Low-Carbon Industrial Future*. https://www.mckinsey.com/capabilities/sustainability/our-insights/africas-green-manufacturing-crossroads-choices-for-a-low-carbon-industrial-future. Accessed January 6, 2023.

McKinsey. 2022. *The Future of African Oil and Gas: Positioning for the Energy Transition*. https://www.mckinsey.com/industries/oil-and-gas/our-insights/the-future-of-african-oil-and-gas-positioning-for-the-energy-transition. Accessed January 6, 2023.

Mentis, Dimitrios, Mark Howells, Holger Rogner, Alexandros Korkovelos, Christopher Arderne, Eduardo Zepeda, Shahid Siyal, et al. 2017. "Lighting the World: The First Application of an Open Source, Spatial Electrification Tool (OnSSET) on Sub-Saharan Africa." *Environmental Research Letters* 12 (8): 085003. https://doi.org/10.1088/1748-9326/aa7b29.

Mihalyi, David, and Thomas Scurfield. 2020. *How Did Africa's Prospective Petroleum Producers Fall Victim to the Presource Curse?* https://documents1.worldbank.org/curated/en/274381599578080257/pdf/How-Did-Africas-Prospective-Petroleum-Producers-Fall-Victim-to-the-Presource-Curse.pdf.

Mulugetta, Yacob, Youba Sokona, Philipp A. Trotter, Samuel Fankhauser, Jessica Omukuti, Lucas Somavilla Croxatto, Bjarne Steffen, et al. 2022. "Africa Needs Context-Relevant Evidence to Shape Its Clean Energy Future." *Nature Energy*, October. https://doi.org/10.1038/s41560-022-01152-0.

NEITI (Nigeria Extractive Industries Transparency Initiative). 2022. *NEITI 2020—Oil and Gas Industry Report*. https://neiti.gov.ng/cms/wp-content/uploads/2022/03/NEITI-OGA-2020-Report.pdf.

NewClimate Institute. 2021. *PROSPECTS+—a Tool for Climate Policy Analysis at the Sectoral and National Level*. https://newclimate.org/sites/default/files/2020/02/PROSPECTS_Methodology.pdf.

Ouedraogo, Nadia S. 2017. "Modeling Sustainable Long-Term Electricity Supply-Demand in Africa." *Applied Energy* 190 (March): 1047–67. https://doi.org/10.1016/j.apenergy.2016.12.162.

Our World in Data. 2022. *Per Capita Electricity Generation, 2021*. https://ourworldindata.org/grapher/per-capita-electricity-generation. Accessed January 6, 2023.

Oyewo, Ayobami, Arman Aghahosseini, Manish Ram, and Christian Breyer. 2020. "Transition towards Decarbonised Power Systems and Its Socio-Economic Impacts in West Africa." *Renewable Energy* 154 (July): 1092–1112. https://doi.org/10.1016/j.renene.2020.03.085.

Oyewo, Ayobami, Dmitrii Bogdanov, Arman Aghahosseini, Theophilus Mensah, and Christian Breyer. 2022. "Contextualizing the Scope, Scale, and Speed of Energy Pathways toward Sustainable Development in Africa." *iScience* 25 (9). https://doi.org/10.1016/j.isci.2022.104965.

Oyewo, Ayomabi, Sebastian Sterl, Siavash Khalili, and Christian Breyer. 2023. "Highly Renewable Energy Systems in Africa—Rationale, Research, and Recommendations." *Joule* 7, 1–34. https://doi.org/10.1016/j.joule.2023.06.004

Pelz, Daniel. 2022. "Germany-Senegal Gas Plan Sparks Outcry." https://www.dw.com/en/germany-senegal-gas-plan-sparks-outcry-from-environmentalists/a-62673733. Accessed January 6, 2023.

PwC Africa Power and Utilities Sector Survey. 2015. *A New Africa Energy World—A More Positive Power Utilities Outlook*. https://www.pwc.com/gx/en/utilities/publications/assets/pwc-africa-power-utilities-survey.pdf.

Ram, Manish, Dmitrii Bogdanov, Arman Aghahosseini, Ashish Gulagi, Solomon A. Oyewo, Michael Child, Upeksha Caldera, et al. 2019. *Global Energy System Based on 100% Renewable Energy—Power, Heat, Transport and Desalination.* Study by Lappeenranta University of Technology and Energy Watch Group. Lappeenranta, Finland & Berlin, Germany. March. Available on http://energywatchgroup.org/wp-content/uploads/EWG_LUT_100RE_All_Sectors_Global_Report_2019.pdf

Rystad Energy. 2019. *BEIS Fossil Fuel Supply Curves*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/863800/fossil-fuel-supply-curves.pdf.

SE4ALL and CPI (Climate Policy Initiative). 2021. *Energizing Finance—Understanding the Landscape 2021*. https://www.seforall.org/system/files/2021-10/EF-2021-UL-SEforALL.pdf.

Semieniuk, Gregor, Philip B. Holden, Jean-Francois Mercure, Pablo Salas, Hector Pollitt, Katharine Jobson, Pim Vercoulen, et al. 2022. "Stranded Fossil-Fuel Assets Translate to Major Losses for Investors in Advanced Economies." *Nature Climate Change* 12 (6): 532–38. https://doi.org/10.1038/s41558-022-01356-y.

Sterl, Sebastian. 2021a. "A Grid for All Seasons: Enhancing the Integration of Variable Solar and Wind Power in Electricity Systems across Africa." *Current Sustainable/Renewable Energy Reports* 8 (August): 274–81. https://doi.org/10.1007/s40518-021-00192-6.

Sterl, Sebastian. 2021b. "Seasons of Power: Streamlining Strategies for Renewable Electricity Generation from Sun, Wind and Water in sub-Saharan Africa." Ph.D. thesis. Brussels, Belgium: Vrije Universiteit Brussel and KU Leuven. http://dx.doi.org/10.13140/RG.2.2.33395.86568/1.

Sterl, Sebastian, and Wim Thiery. 2022. "La Faisabilité du Solaire PV pour Remplacer la Centrale Hydroélectrique de Koukoutamba en Guinée-Étude Quantitative." Brussels, Belgium: Vrije Universiteit Brussel. https://researchportal.vub.be/files/92042463/VUB_2022_La_faisabilit_du_solaire_PV_pour_remplacer_la_centrale_hydro_lectrique_de_Koukoutamba_en_Guin_e_tude_quantitative_num_rique_.pdf.

Sterl, Sebastian, Jing Zhang, Markus Hagemann, Lindee Wong, Tom Berg, Yvonne Deng, Jeroen de Beer, et al. 2017. "Manufacturing a Low-Carbon Society: How Can We Reduce Emissions from Cement and Steel?" https://climateanalytics.org/media/memo_decarb_industry_final.pdf.

Sterl, Sebastian, Inne Vanderkelen, Celray James Chawanda, Daniel Russo, Robert J. Brecha, Ann van Griensven, Nicole P. M. van Lipzig, and Wim Thiery. 2020. "Smart Renewable Electricity Portfolios in West Africa." *Nature Sustainability* 3 (9): 710–19. https://doi.org/10.1038/s41893-020-0539-0.

Sterl, Sebastian, Dalia Fadly, Stefan Liersch, Hagen Koch, and Wim Thiery. 2021. "Linking Solar and Wind Power in Eastern Africa with Operation of the Grand Ethiopian Renaissance Dam." *Nature Energy* 6 (4): 407–18. https://doi.org/10.1038/s41560-021-00799-5.

Sterl, Sebastian, Bilal Hussain, Asami Miketa, Yunshu Li, Bruno Merven, Mohammed Bassam Ben Ticha, Mohamed A. Eltahir Elabbas, Wim Thiery, and Daniel Russo. 2022. "An All-Africa Dataset of Energy Model 'Supply Regions' for Solar Photovoltaic and Wind Power." *Scientific Data* 9: 664. https://doi.org/10.1038/s41597-022-01786-5.

Sweerts, Bart, Francesco Dalla Longa, and Bob van der Zwaan. 2019. "Financial De-risking to Unlock Africa's Renewable Energy Potential." *Renewable and Sustainable Energy Reviews* 102 (March): 75–82. https://doi.org/10.1016/j.rser.2018.11.039.

Taliotis, Constantinos, Abhishek Shivakumar, Eunice Ramos, Mark Howells, Dimitris Mentis, Vignesh Sridharan, Oliver Broad, and Linus Mofor. 2016. "An Indicative Analysis of Investment Opportunities in the African Electricity Supply Sector—Using TEMBA (The Electricity Model Base for Africa)." *Energy for Sustainable Development* 31 (April): 50–66. https://doi.org/10.1016/j.esd.2015.12.001.

Trimble, Chris, Masami Kojima, Ines Perez Arroyo, and Farah Mohammadzadeh. 2016. "Financial Viability of Electricity Sectors in Sub-Saharan Africa—Quasi-Fiscal Deficits and Hidden Costs." Policy Research Working Paper 7788. Washington, DC: World Bank. https://openknowledge.worldbank.org/bitstream/handle/10986/24869/WPS7788.pdf?sequence=4&isAllowed=y.

Trotter, Philipp A., and Aoife Brophy. 2022. "Policy Mixes for Business Model Innovation: The Case of Off-Grid Energy for Sustainable Development in Sub-Saharan Africa." *Research Policy* 51 (6): 104528. https://doi.org/10.1016/j.respol.2022.104528.

Twesigye, Peter. 2022. "Structural, Governance, & Regulatory Incentives for Improved Utility Performance: A Comparative Analysis of Electric Utilities in Tanzania, Kenya, and Uganda." *Utilities Policy* 79 (December): 101419. https://doi.org/10.1016/j.jup.2022.101419.

UN (United Nations). 2022. *Revision of World Population Prospects*. United Nations Department of Economic and Social Affairs. https://population.un.org/wpp/. Accessed January 6, 2023.

UNECA (United Nations Economic Commission for Africa). 2020. *Natural Gas: Africa's Energy Transition Accelerator*. https://repository.uneca.org/bitstream/handle/10855/43686/b11982755.pdf?sequence=1&isAllowed=y. Accessed November 7, 2022.

UNECA. 2022. "Zambia and DRC Sign Cooperation Agreement to Manufacture Electric Batteries." https://www.uneca.org/stories/zambia-and-drc-sign-cooperation-agreement-to-manufacture-electric-batteries. Accessed January 6, 2023.

UNEP (United Nations Environment Programme). 2020. *Used Vehicles and the Environment. A Global Overview of Used Light Duty Vehicles: Flow, Scale and Regulation*. https://www.unep.org/resources/report/global-trade-used-vehicles-report Accessed November 7, 2022.

UNFCCC (United Nations Framework Convention on Climate Change). 2021. "New Financial Alliance for Net Zero Emissions Launches." https://unfccc.int/news/new-financial-alliance-for-net-zero-emissions-launches. Accessed November 7, 2022.

USGS (U.S. Geological Survey). 2022. *2017–2018 Minerals Yearbook—Guinea*. https://pubs.usgs.gov/myb/vol3/2017-18/myb3-2017-18-guinea.pdf.

WEForum (World Economic Forum). 2022. *How Africa Could Become a Global Hydrogen Powerhouse*. https://www.weforum.org/agenda/2022/07/africa-hydrogen-iea/.

World Bank. 2022a. *Agricultural Land (Sq. Km)*. (Database.) https://data.worldbank.org/indicator/AG.LND.AGRI.K2.

World Bank. 2022b. *Fertilizer Consumption (% of Fertilizer Production)*. (Database.) https://data.worldbank.org/indicator/AG.CON.FERT.PT.ZS.

World Bank. 2022c. *Fertilizer Consumption (Kilograms per Hectare of Arable Land)*. (Database.) https://data.worldbank.org/indicator/AG.CON.FERT.ZS.

World Bank Group. 2020. *Global Wind Atlas*. https://globalwindatlas.info/. Accessed November 7, 2022.

World Steel Association. 2021. *2021 World Steel in Figures*. https://worldsteel.org/wp-content/uploads/2021-World-Steel-in-Figures.pdf.

Wu, Grace C., Ranjit Deshmukh, Kudakwashe Ndhlukula, Tijana Radojicic, Jessica Reilly-Moman, Amol Phadke, Daniel M. Kammen, and Duncan S. Callaway. 2017. "Strategic Siting and Regional Grid Interconnections Key to Low-Carbon Futures in African Countries." *Proceedings of the National Academy of Sciences* 114 (15): E3004–12. https://doi.org/10.1073/pnas.1611845114.

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World Resources Institute is a global research organization that turns big ideas into action at the nexus of environment, economic opportunity, and human well-being.

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Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

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The ETC (Energy Transitions Commission) is a global coalition of leaders from across the energy landscape committed to achieving net-zero emissions by mid-century, in line with the Paris climate objective of limiting global warming to well below 2°C and ideally to 1.5°C.

The ETC's commissioners come from a range of organizations—energy producers, energy-intensive industries, technology providers, finance players, and environmental nongovernmental organizations—which operate across developed and developing countries and play different roles in the energy transition. This diversity of viewpoints informs the ETC's work, whose analyses are developed with a systems perspective through extensive exchanges with experts and practitioners.

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