OXFAM
RESEARCH BACKGROUNDER

The energy challenge in sub-Saharan Africa: A guide for advocates and policy makers

Part 1: Generating energy for sustainable and equitable development

Nkiruka Avila, Juan Pablo Carvallo, Brittany Shaw, and Daniel M. Kammen

2017

OXFAM
RESEARCH BACKGROUNDER

CONTENTS

OXFAM'S RESEARCH BACKGROUNDERS

Series editor: Kimberly Pfeifer

Oxfam's Research Backgrounders are designed to inform and foster discussion about topics critical to poverty reduction. The series explores a range of issues on which Oxfam works—all within the broader context of international development and humanitarian relief. The series was designed to share Oxfam's rich research with a wide audience in hopes of fostering thoughtful debate and discussion. All Backgrounders are available as downloadable PDFs on our website, oxfamamerica.org/research, and may be distributed and cited with proper attribution (please see following page).

Topics of Oxfam's Research Backgrounders are selected to support Oxfam's development objectives or key aspects of our policy work. Each Backgrounder represents an initial effort by Oxfam to inform the strategic development of our work, and each is either a literature synthesis or original research, conducted or commissioned by Oxfam America. All Backgrounders have undergone peer review.

Oxfam's Research Backgrounders are not intended as advocacy or campaign tools; nor do they constitute an expression of Oxfam policy. The views expressed are those of the authors—not necessarily those of Oxfam. Nonetheless, we believe this research constitutes a useful body of work for all readers interested in poverty reduction.

For a full list of available Backgrounders, please see the "Research Backgrounder Series Listing" section of this report.

Author information and acknowledgments

Professor Daniel M. Kammen is the founding director of the Renewable and Appropriate Energy Laboratory (RAEL) at the University of California, Berkeley. He is also the science envoy to the U.S. State Department.

Nkiruka Avila is a Ph.D. student in the Energy and Resources Group at the University of California, Berkeley, and a research affiliate at the Lawrence Berkeley National Lab.

Juan Pablo Carvallo is a Ph.D. candidate in the Energy and Resources Group at UC Berkeley and a senior scientific engineering associate at Lawrence Berkeley National Lab.

Britt Shaw is a master’s student in the Energy and Resources Group at UC Berkeley.

This work was generously funded by the Nathan Cummings Foundation. The report benefited greatly from the comments and inputs of Sasanka Thilakasiri, James Morrissey, Kiri Hanks, Yacob Mulugetta, Tracy Carty, Paulina Jaramillo, Heather Coleman, and Kimberly Pfeifer.

Citations of this paper

Please use the following format when citing this paper:

Avila, N., Carvallo, J. P., Shaw, B. and Kammen, D. M, The energy challenge in sub-Saharan Africa: A guide for advocates and policy makers: Part 1: Generating energy for sustainable and equitable development. Oxfam Research Backgrounder series (2017): https://www.oxfamamerica.org/static/media/files/oxfam-RAEL-energySSA-pt1.pdf

Author correspondence should be addressed to:
Professor D. M. Kammen
Renewable and Appropriate Energy Laboratory
Energy and Resources Group
University of California
Berkeley, CA 94720 USA
kammen@berkeley.edu | URL: http://rael.berkeley.edu

ACRONYMS AND ABBREVIATIONS

GW	gigawatt
ICT	information and communication technology
IEA	International Energy Agency
IPP	independent power producer
kWh	kilowatt hour
LCOE	levelized cost of electricity
LCPDP	least-cost power development plan
LPG	liquid petroleum gas
MMBtu	1 million British thermal units
MTP	medium-term power development plan
PV	photovoltaic
SHS	solar home system
TWh	terawatt hour

EXECUTIVE SUMMARY

Sub-Saharan Africa, home to more than 950 million people, is the most electricity-poor region in the world. More than 600 million people lack access to electricity, and millions more are connected to an unreliable grid that does not meet their daily energy service needs. Most countries in this region have electricity access rates of about 20%, and two out of three people lack access to modern energy services. The average annual electricity consumption in the sub-Saharan residential sector is 488 kilowatt hours (kWh) per capita—equivalent to about 5% the consumption of the United States. The International Energy Agency (IEA) estimates that electricity demand in sub-Saharan Africa grew by about 35% from 2000 to 2012 to reach 352 terawatt hours (TWh), and it forecasts the total demand for electricity in Africa to increase at an average rate of 4% a year through 2040. Demand estimates that include self-generation, such as diesel generators, report even higher figures: 423 TWh in 2010. To meet this growing demand, the region will need to significantly expand its installed generation capacity and make extensive upgrades to the power grid. At the current pace of electrification and population growth, more than half a billion people are expected to remain without access to electricity by 2040, and full electricity access in the region is not estimated to be accomplished until 2080. Hence, sub-Saharan Africa is burdened with a complex and persistent electricity gap.

The electricity gap refers to both the supply-demand mismatch in grid-connected regions and the lack of access in off-grid regions. Closing the electricity gap in sub-Saharan Africa is a multidimensional challenge with important implications for how to frame the region's energy problem as a whole.

Sub-Saharan Africa has high income and wealth inequality, which leads to vast differences in consumers' desire and willingness to pay for electricity. Its countries display large disparities in electricity costs, with South Africa and Zambia among the lowest, and Djibouti and Gabon among the highest. Access to electricity is also highly unequal, even among people who are connected to the grid. Some people cannot afford to consume electricity despite being connected. Therefore, they cannot consume enough electricity to make use of modern energy services. They may also suffer disproportionately high levels of service interruption, with no ability to depend on expensive on-site diesel generators like wealthier people in the same region. The electronic appliances the region's consumers will purchase—many for the first time—will be more efficient than the current stock in many wealthier economies. Hence, the pace, level, and profile of electricity demand in sub-Saharan Africa will evolve differently. There are technological, geographical, cultural, and social distinctions that suggest the region should define its own target standard of living and type of energy services to be pursued, rather than comparing itself with wealthier countries.

Persistent electricity scarcity has crippled the region's economic growth and prevented it from attaining several of its health and education development goals. Causes of this scarcity include lack of generation capacity to supply power to grid-connected regions, absence of proper grid infrastructure to deliver this power, regulatory impediments to providing steady revenue to maintain and invest in new generation capacity, and dispersity of population in remote areas. As of 2012, sub-Saharan Africa's installed generation capacity was a mere 90 GW—about 0.1 kW per capita—in stark contrast with wealthier economies that have installed capacities ranging from 1.0 to 3.3 kW per capita. The region's inability to provide reliable electricity has led to prolific growth of inefficient and expensive on-site self-generation in industrial, commercial, and even residential sectors.

This lack of systematic planning for the power sector has resulted in a system with high transmission and distribution losses (averaging 18% across the region when South Africa is excluded), and created a high dependence on large dams and expensive diesel plants. The region's dependence on fossil fuel plants creates a multifaceted problem of supply and price variability, with fuel producers curtailing supply under low prices and consumers suffering economic losses during periods of high prices. In addition, climate change is projected to have a substantial impact on the reliability of hydropower resources in sub-Saharan Africa. Erratic rainfall patterns and prolonged droughts can reduce hydroelectric output and force extended outages. While the region contributes the least to greenhouse gas emissions, it is most vulnerable to climate change impacts such as droughts and reduced agricultural yields.

This complex challenge presents an opportunity for sub-Saharan countries to design low-fuel, low-carbon power systems based on wind, geothermal, and solar technologies and to use responsive and efficient demand management strategies.

The region is home to abundant fossil and renewable energy sources. The technical potential for generation capacity is estimated at about 10,000 GW of solar power, 350 GW of hydroelectricity, and 400 GW of natural gas, totaling more than 11,000 GW. The limiting factors in the region's electricity development are effective technical, financing, and policy mechanisms to enable the development of these resources. In addition, the region's lack of grid infrastructure can be transformed into an opportunity to lead the way toward better-designed, more efficient, sustainable power systems without being hindered by legacy carbon-intensive assets. Both private and public stakeholders have a window of opportunity to determine how best to coordinate energy solutions at the point of use, mini-grid, and centralized grid levels. Mechanisms should be put in place to facilitate grid extension and micro-grid deployment in order to reach unconnected regions. Utility and tariff structures must be fair, stable, and sustainable to ensure cost-effective and reliable delivery to end users, as well as proper maintenance of valuable energy infrastructure.

Filling the electricity gap with renewable sources will entail economic and environmental trade-offs because of the region's unique combination of challenges and opportunities. A promising way to facilitate this development is through regional power pools that allow countries to aggregate resources and extend grids across national borders, capitalizing on regional diversity in resources and demand. Four regional power pools already exist, but only about 7% of electricity is traded across international borders, mostly through the South African Power Pool. Facilitating increased use of the region's four power pools could save more than $50 billion in capital investments in the power sector. Power pools could also facilitate additional strategies to incorporate large amounts of variable renewable generation such as the use of existing reservoir hydropower to provide storage, the deployment of novel chemical and mechanical storage technologies, and the adoption of widespread demand response programs across the region.

Designing, testing, and assessing different expansion scenarios for sub-Saharan Africa is paramount to finding the optimal combination of supply, transmission, storage, and demand-side resources to fuel development and growth for the coming decades. Countries need to develop and adopt a host of data-driven integrated modeling tools for systems-level planning and operation at an unprecedented scale. Governments need to partner with academic institutions and private sector stakeholders to produce data in the quality and quantity required to provide decision makers with the right inputs for these modeling tools.

In this report, we design an open-access power system model and analyze optimal pathways for expanding supply capacity in two case study countries: Kenya and Nigeria. We compare the average costs of various expansion scenarios for achieving reliable and affordable power by 2035 and explore issues such as integration of variable renewable resources, improvements in electricity access, impacts of reliability, and the role of decentralized energy resources.

The case studies show that renewables are now cost competitive and that fuels such as natural gas can play a role in providing system flexibility until grid storage costs decline. The analysis shows that fuel choices should be considered cautiously—particularly coal, which is shown to be a costly pathway to electrification in Kenya and Nigeria. The case studies also show that the scale of centralized generation expansion required to meet moderate load growth by 2035 is significant compared with historical investments in power systems and the rate of system expansion in many countries in the region. Current investment in sub-Saharan electricity systems is about US$8 billion a year. This is inadequate to overcome the existing infrastructure challenge, to expand access and coverage, and to meet the growth in demand. The model estimates that Nigeria will have to install at least an additional 36 GW by 2035 to keep up with grid-based load growth alone, and Kenya will have to install at least 17 GW. This is about five times the current operational capacity in each country. Therefore, achieving full electricity access will require combining many pathways and strategies, such as synergies between centralized and distributed energy systems, bolstered financial support and investments, and improved institutional capacity and management.

Though challenging, these results reveal opportunities to increase the use of clean energy and build intra- and international cooperation in Africa. While models only illustrate opportunities, the signs are hopeful that if energy access and sustainable development are raised as continent-wide priorities, Africa is primed for an energy transformation. A number of important conclusions emerge from this assessment.

Key observations are the following:

- While sub-Saharan Africa has significant fossil fuel resources, many of which are the focus of domestic and international "resource races," investments in and use of fossil fuels should be judicious given that
  - the exploitation of fossil fuels, even in energy-limited countries, often comes at the expense of the development of sustainable energy sources; and
  - decades of experience show that fossil fuel energy development does little to increase energy access, which is lower in sub-Saharan Africa than in any other region.
- Africa has exceptional solar, wind, geothermal, and biomass resource potential, both on a per capita basis and in terms of resource diversity. Africa could thus achieve high levels of energy services with very low carbon emissions.
- Advances in smart grids and information and communication technologies (ICTs) will enable the region to take full advantage of its exceptional renewable resources.
- Successfully integrating large shares of variable renewable resources will require high grid flexibility, currently hindered by the difficulty of operationalizing regional power pools and the high cost of energy storage.
- Operational power pools combined with strategic policies and actionable targets could quicken the pace of electrification across the region.

- As these challenges are resolved, fossil fuels, particularly natural gas, will likely remain a part of the region's transition to a low-carbon electricity grid.

These observations lead to the following actionable conclusions:

- Lack of data is hindering analysis of future grid designs in many countries in the region. The development of robust planning tools that have relatively low data requirements will permit the widest vetting of renewable energy projects based on their energy, social, and environmental costs and benefits.

- Investment in renewable energy is proving a more sustainable and cost-effective path to meeting Africa's dual challenges of economic empowerment and energy access.

- A clean energy path benefits significantly from well-functioning regional power pools. National efforts to develop clean energy transition plans and policies aligning on-grid and off-grid energy service delivery are key, but added regional work—via regional power pools—can speed progress on meeting the joint goals of national and regional energy sufficiency, as well as full energy access across Africa.

- Worldwide, too little attention has been paid to ways of coordinating and integrating off-grid, mini-grid, and large utility-scale power systems. For African countries and individuals, the benefits of such a systems nexus can be transformative.

Text Box 1: An electricity grid lexicon

A number of industry terms related to the technical, economic, management, and environmental elements of the power system are defined here.

Capacity factor: the ratio of a power plant's actual generation output over a period of time to its potential output (also known as nameplate capacity) if the power plant were to operate at full nameplate capacity continuously over the same period of time.

Captive generation: localized sources of power such as diesel generators set up by individuals or small communities for personal use. It is also known as self-generation.

Contingency reserves: extra generation that is kept available in the case of generator or transmission outage.

Curtailment: the reduction in a power plant's scheduled output due to excess generation and transmission congestion. Typically there is no compensation for the reduction in output, and it may decrease the plant's profitability.

Demand response: the shifting of loads by getting end-users to shut off appliances and larger industrial machines at peak times and to run those machines at specific off-peak hours instead, changing the load profile to match the generation supply.

Demand uncertainty: all power systems are planned with a degree of uncertainty of the load, and the demand forecasts are refined closer to the day of operation, within hours and minutes.

Dispatchable power: electricity from generators that can adjust their power output according to grid operator requests. Dispatchable plants have the ability to dispatch their power over time frames from minutes to one hour.

Distributed generation: small-scale energy technologies (usually modular generators) to produce electricity close to load centers and end users

Electricity grid: an interconnected network that delivers electricity to consumers. The power is delivered from large generators through long-distance high-voltage transmission lines to distribution stations where the power is stepped down to lower voltages and connected to individual customers. This design is referred to as a centralized grid.

Energy balance: the match between supply and demand that grid operators must maintain at all times in order to avoid electricity blackouts. Achieving this balance requires dispatchable and flexible generators and storage.

Energy efficiency: the delivery of more services for the same energy input or the delivery of the same services for less energy input. This is a way of managing and restraining the growth in energy consumption.

Energy storage: various technologies such as batteries, pumped hydropower, and flywheels that can store electrical energy and smooth electricity supply to enable constant energy balance in a grid.

Flexible generation: the ability of power plants to ramp power production up and down quickly and efficiently to respond to changes in energy demand.

Flexible transmission: the ability of electricity networks to limit bottlenecks in power transmission and to allow for energy balancing in a larger area by drawing on neighboring networks.

Fossil fuels: nonrenewable sources of energy that have developed from buried organic matter in the earth over millions of years. They include oil, natural gas, and coal.

Grid flexibility: the ability of a power system to respond to changes in demand and supply—is a characteristic of all power systems. Flexibility is especially critical with higher levels of grid-connected variable renewable energy (primarily, wind and solar).

Intermittent power: the variable output of renewable sources such as solar and wind, owing to changing weather conditions. Their intermittent power supply requires storage and/or fast-acting generators to smooth the output.

Levelized cost of electricity: the net present value of the unit cost (capital and variable) of electricity over the lifetime of a generating asset. It is used as a proxy for the average price that the generating asset must receive in a market to break even over its lifetime.

Load duration curve: electricity demand sorted in descending order of magnitude over a time period.

Mini-grid/micro-grid: any grid that is not linked to the main central grid in the country in which it is located.

Net load: the remaining electricity demand that must be supplied by the conventional generation fleet after all of the variable renewable energy has been consumed.

Non-spinning reserves: the additional generating capacity that is not currently connected to the system but can be brought online after a short delay using fast-start dispatchable generators or through imports.

Operating reserves: the generating capacity available to the system operator within a short interval of time to meet demand in case a generator goes down or there is another disruption to the supply. It is made up of spinning and non-spinning reserves.

Ramps: a generation plant's rate of change of dispatchable power to follow changes in demand. A plant may ramp up to respond to rises in demand or failure of other generators, or ramp down during low load hours.

Renewable energy: energy that is derived from natural processes and constantly replenished. In its various forms, it derives directly or indirectly from the sun or from heat generated deep within the earth. It includes energy generated from solar, wind, biomass, geothermal, hydropower, and ocean resources, as well as biofuels and hydrogen derived from renewable resources.

Renewables integration: high penetration of renewables on the grid presents challenges because conventional grid designs are built to transmit power from large dispatchable and controllable generators to loads. To avoid blackouts, energy generated and consumed on the grid must be equal at every instant. Wind and solar generators are not dispatchable and controllable as they depend on weather patterns. Therefore, a grid with large amounts of renewables will require storage and fast-acting dispatchable generators to maintain grid balance.

Spinning reserves: the additional generating capacity available to grid operators to meet unforeseen changes in demand by increasing the power output of generators that are already connected to the power system.

Turndown: the use of generators at low output levels. Dispatchable generators may be required to turn down to low output for a period of time and must also have the ability to increase its generation quickly again.

1. INTRODUCTION

Sub-Saharan Africa faces two major energy challenges: inadequate energy access and climate change. It must attain 100% electricity access and develop clean energy systems to mitigate climate change impacts. It is the most electricity-poor region in the world: more than 600 million people lack access to electricity, and several million people are connected to an unreliable grid that does not meet their daily energy service needs. Most countries in this region have average electricity access rates of about 20%, and two out of three people lack access to modern energy services. Demand estimates that include self-generation, such as diesel generators, in sub-Saharan Africa report electricity demand to be 423 TWh in 2010 (Castellano et al., 2015). The International Energy Agency (IEA) estimates that electricity demand in sub-Saharan Africa grew by about 45% from 2000 to 2012 and expects the total demand for electricity in Africa to increase at an average rate of 4% a year until 2040 (IEA, 2014). To meet this demand, the region must significantly expand its installed generation capacity and make extensive upgrades to its power grid. With the current pace of electrification and population growth, more than half a billion people are expected to remain without access to electricity by 2040 (IEA, 2016) and full electricity access in the region is only estimated to be accomplished by 2080 (Africa Progress Panel, 2015). Hence, sub-Saharan Africa is burdened with a complex and persistent electricity gap.

The challenge of closing the electricity gap in sub-Saharan Africa while limiting greenhouse gas emissions is the context that frames this report. The report sets out to review the generation potential available from different energy sources and then looks at the challenges and opportunities presented by different electricity expansion pathways. The work includes models of the electricity systems in two countries: Nigeria and Kenya, in which the least-cost investment pathway is assessed under a number of different scenarios. The report focuses on explaining the technical and institutional challenges that characterize different energy pathways and in this respect the report is intended as a guide to advocates and policy-makers.

This work is based on a six-month review of the literature on electricity systems and options in sub-Saharan Africa as well as modeling efforts assessing Kenya and Nigeria. This report (Part 1) on closing the electricity gap in sub-Saharan Africa is intended to complement another Oxfam report exploring the particular challenges related to promoting energy access and addressing energy poverty. That report, referenced as Part 2, can be found where this report was downloaded.

UNDERSTANDING SUB-SAHARAN AFRICA'S ELECTRICITY GAP

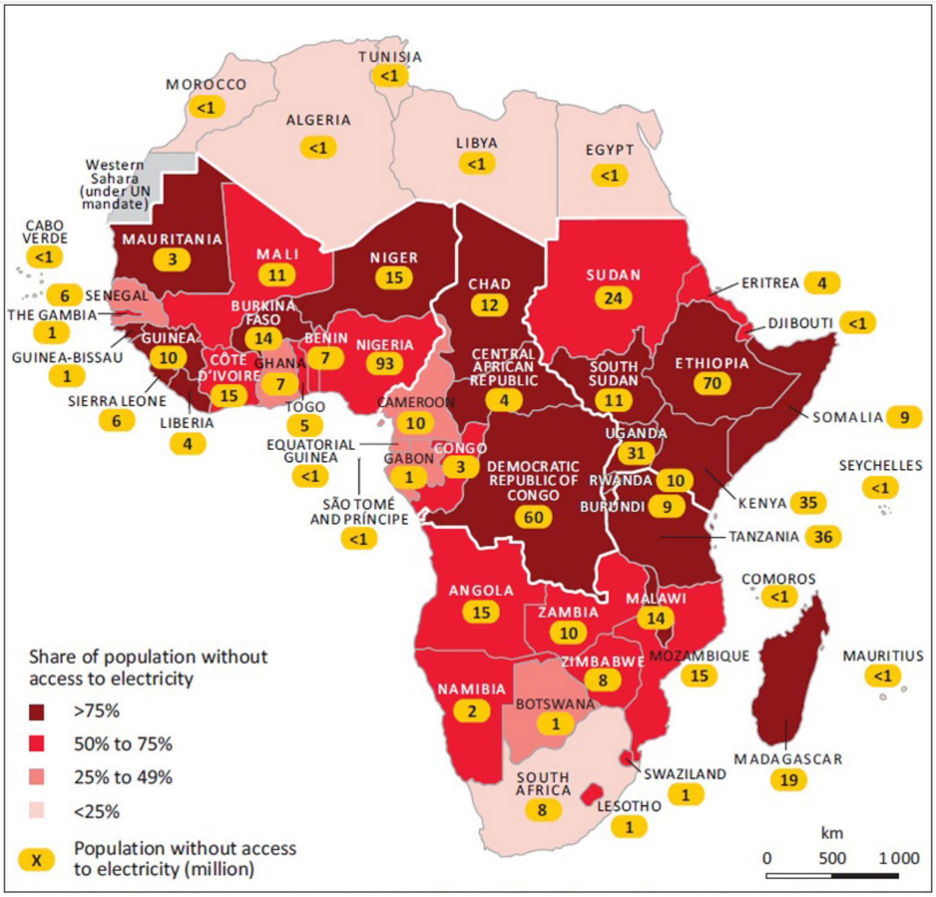
Sub-Saharan Africa faces an electricity gap in two senses: a mismatch between supply and demand in grid-connected regions, and a lack of access in off-grid regions. Closing sub-Saharan Africa's electricity gap is a multidimensional challenge with important implications for how to frame the region's energy problem as a whole.

Sub-Saharan Africa has high income and wealth inequality (IEA, 2014), which results in vast differences in consumers' desire and willingness to pay for electricity. The cost of electricity also varies widely within the region, with South Africa and Zambia being among the lowest and Djibouti and Gabon being among the highest. Even among people who are connected to the grid, there are disparities in consumption. Despite being connected to the grid, some people cannot afford to consume electricity and thus cannot make use of modern energy services. They may also suffer disproportionately higher levels of service interruption, with no ability to depend on expensive on-site diesel generators like wealthier people in the same region.

Also, the electronic appliances the region's consumers will purchase—many for the first time—will be more efficient than the current stock in many wealthier economies. Hence, the pace, level, and profile of electricity demand in the region will evolve differently. There are technological, geographical, cultural, and social distinctions that suggest sub-Saharan Africa should define its own target standard of living and type of energy services to be pursued, rather than comparing itself with wealthier countries.

In sub-Saharan Africa, the average annual electricity consumption is 488 kWh per capita—equivalent to about 5% of U.S. per capita consumption (World Bank, 2014). This average has been pushed up by South Africa's high electricity access rates. When South Africa is excluded, annual electricity consumption is only about 150 kWh per capita (World Bank, 2014). These estimates, however, may be conservative owing to the latent demand that remains unmet as a result of lack of grid access in rural areas, and unreliable grids and epileptic power supply in urban grid-connected areas. The prolific use of expensive on-site diesel generators indicates significant latent demand, but it is difficult to accurately measure and account for these generators in the region.

Figure 1: Rates of access to electricity and total populations without access to electricity



Source: IEA, 2014.

Sub-Saharan Africa has a unique opportunity to expand its generation capacity without exacerbating climate change owing to its abundant renewable resources. At the November 2016 United Nations Climate Change Conference in Morocco, 47 members of the Climate Vulnerable Forum (many of which are in sub-Saharan Africa) pledged to strive to achieve 100% domestic renewable energy production as rapidly as possible (Climate Vulnerable Forum, 2016). Renewable energy is key to solving both the region's energy access and climate change challenges. The limiting factor in the region's electricity development is effective technical, financing, and policy mechanisms to enable the region to develop these resources. Its lack of grid infrastructure can be transformed into a leadership opportunity to develop better-designed and more efficient power systems without being hindered by legacy carbon-intensive assets. Governments and private sector stakeholders have made concerted efforts to promote the use of micro-grids and other distributed energy resources to reach unelectrified regions, and these efforts have inadvertently resulted in the juxtaposition of centralized and distributed technologies as opposing efforts. The two should be regarded, however, as complementary. When centralized and distributed grids are built with the intent to integrate and connect them in the future, they can have strategic synergies. Effective frameworks must be put in place to facilitate this. Finally, utility and tariff structures can be reformed to reflect fair and stable rates that ensure reliable delivery to end-users.

The region will face significant economic, environmental, political, and operational challenges and trade-offs on the way to achieving these goals. To understand the scale of these challenges, we designed an open-access power system model to analyze optimal pathways for expanding supply capacity in two case study countries: Kenya and Nigeria. This analysis compares the average costs of various expansion scenarios for achieving reliable and affordable power by 2035 and explores the roles of renewables in the electricity mix under various demand growth, and policy conditions.

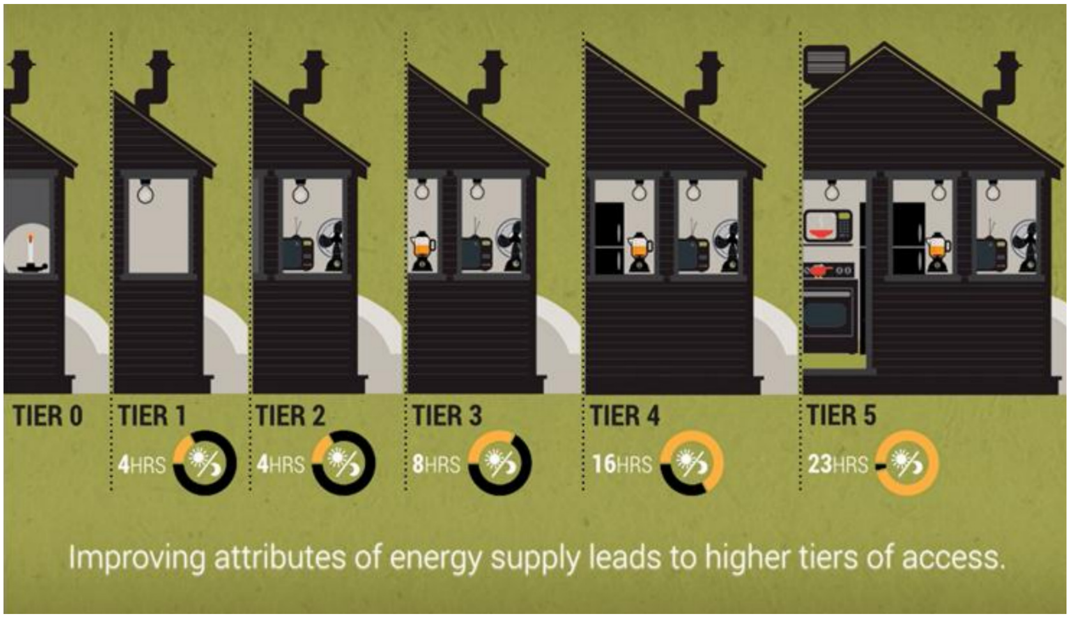
DEFINING ENERGY ACCESS

One of the challenges in addressing the electricity gap in sub-Saharan Africa is that grid connection rates there do not present a holistic picture of actual access to modern energy services. It is common for countries to have a high rate of grid connection combined with a low quality of electricity supply (see Nigeria in Figure 12).

Energy access is intertwined with complex socioeconomic factors that cannot be measured using a binary "connected/not connected" approach. Measuring who has access to energy, particularly electricity, requires a holistic understanding of the quality of access and how it affects socioeconomic development. It calls for answering questions such as, Is there a connection to the central grid? How affordable are the grid connection and its electricity supply? How reliable and predictable is the electricity supply? How safe is the electricity supply? In response to this complexity, the World Bank proposed a multi-tier framework for defining and measuring access to energy (Bhatia & Angelou, 2015), based on several principles:

1. Energy access should be measured by usability, reliability, and affordability defined from the user's perspective.
2. Energy access involves a spectrum of service levels experienced by households and individuals.
3. Energy access can be achieved through a variety of technologies, so its measure should be technology-neutral.

Figure 2: The multi-tier energy access framework



Source: Bhatia & Angelou, 2015.

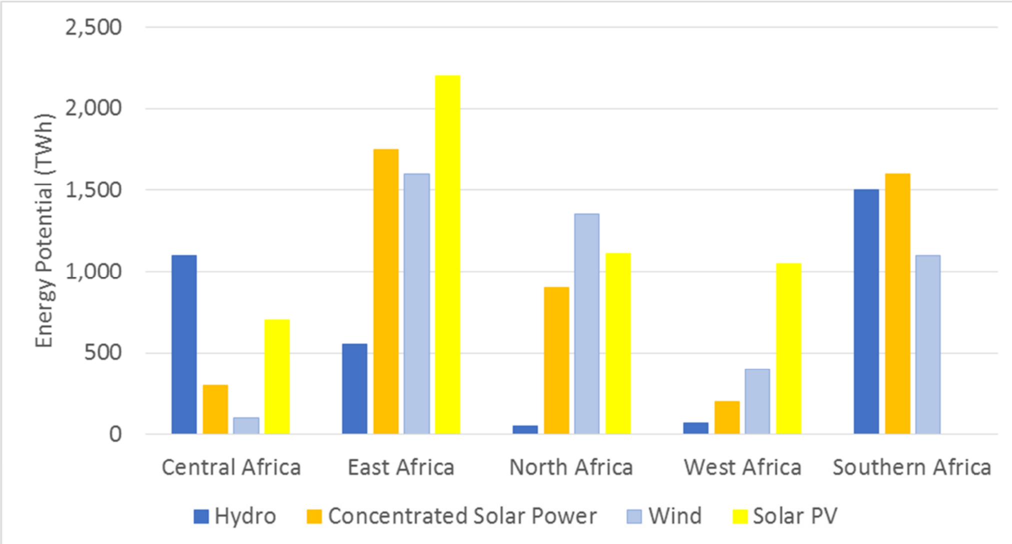
2. RESOURCE POTENTIAL IN SUB-SAHARAN AFRICA

Sub-Saharan Africa has abundant renewable and fossil energy resources that have yet to be developed to meet its electricity demand. Its technical generation capacity potential is estimated to be 11,000 gigawatts (GW), largely from renewables (Figure 3).

POTENTIAL RENEWABLE AND FOSSIL RESOURCES

All of the countries across the region have high solar potential, totaling about 10,000 GW, and the technical potential for solar photovoltaic alone has been estimated at 6,500 terrawatt hours (TWh) a year (Cartwright, 2015). Most of its coastal countries have high wind potential, totaling about 109 GW. The East Africa Rift Valley offers an estimated 15 GW of geothermal capacity, mainly in Ethiopia and Kenya. Because the region is home to the Congo and the Nile Rivers, among the world's longest rivers, it also has some of the greatest hydropower resources in the world. Its exploitable hydropower is estimated at about 350 GW, located mainly in Angola, Cameroon, the Democratic Republic of Congo (DRC), Ethiopia, and Gabon. Its fossil energy resources include recent oil and gas discoveries, and it has about 400 GW of natural gas potential. Coal resources are estimated at 300 GW, mainly in Botswana, Mozambique, and South Africa (Castellano et al., 2015). Notably, however, some low-access countries like Angola and Nigeria have a well-developed petroleum production infrastructure that has not translated into a reliable electricity supply (Figure 1).

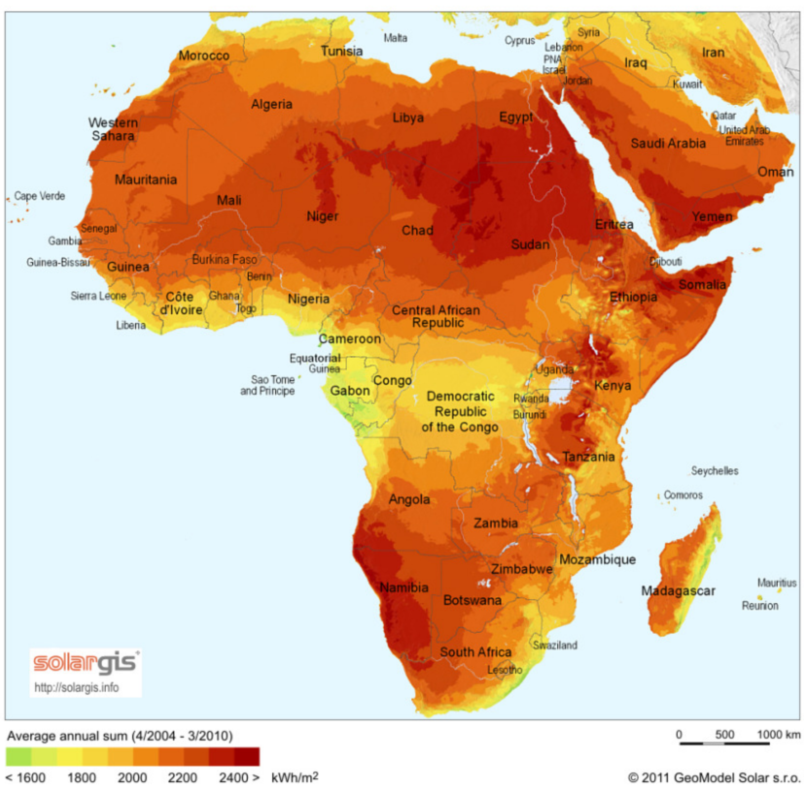
Figure 3: Abundant renewable energy potential in Sub-Saharan Africa



Source: Cartwright, 2015.

Figure ***4*** shows the spatial distribution of solar irradiation in Africa, highlighting high-potential areas of concentrated solar power and photovoltaic development.

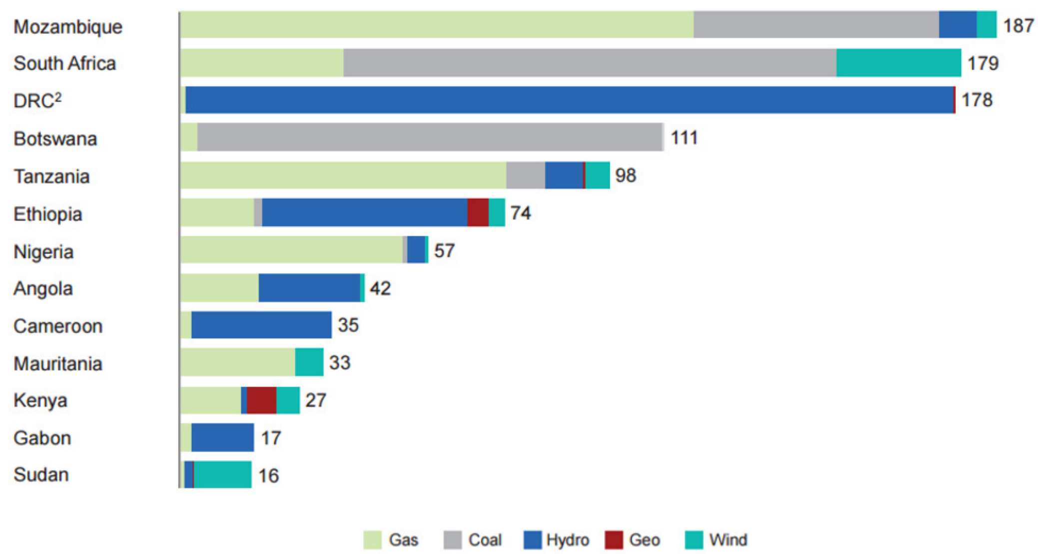
Figure 4: Solar irradiation across Africa



Source: GeoSUN Africa, 2011.

Figure *5* shows that the largest electricity generation potential exists in Central and Southern Africa, comprising mostly hydropower, coal, and natural gas. Geothermal potential exists mainly in Eastern Africa, in Ethiopia, Kenya, and Tanzania. This concentration of resources in different zones highlights the importance of regional cooperation, especially because some of the regions with the greatest regional generation potential do not have the highest demand (Castellano et al., 2015).

Figure 5: Electricity generation potential (GW) by technology

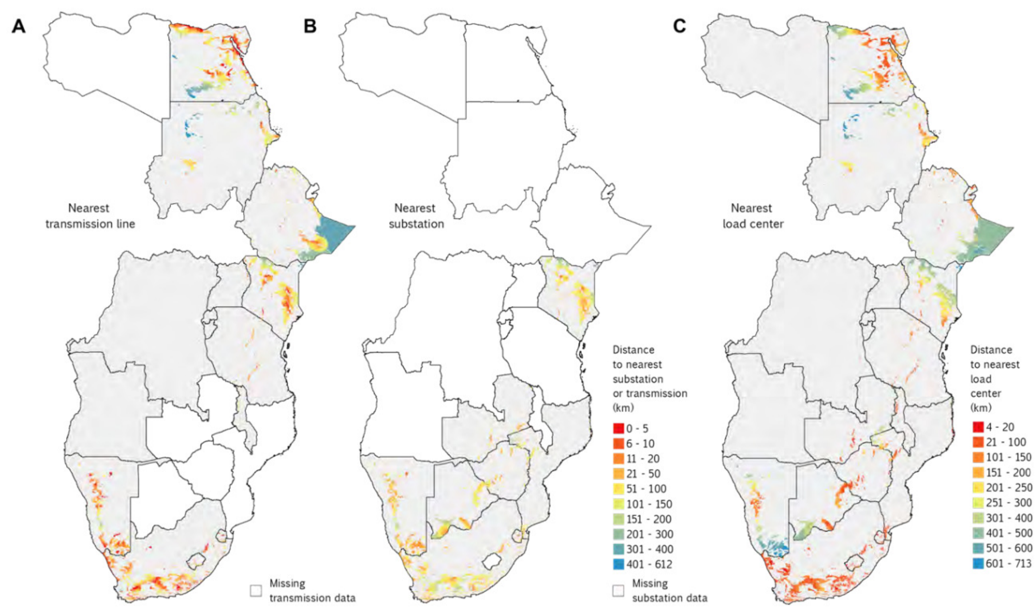


Source: (Castellano et al., 2015).

RENEWABLE ENERGY ZONES

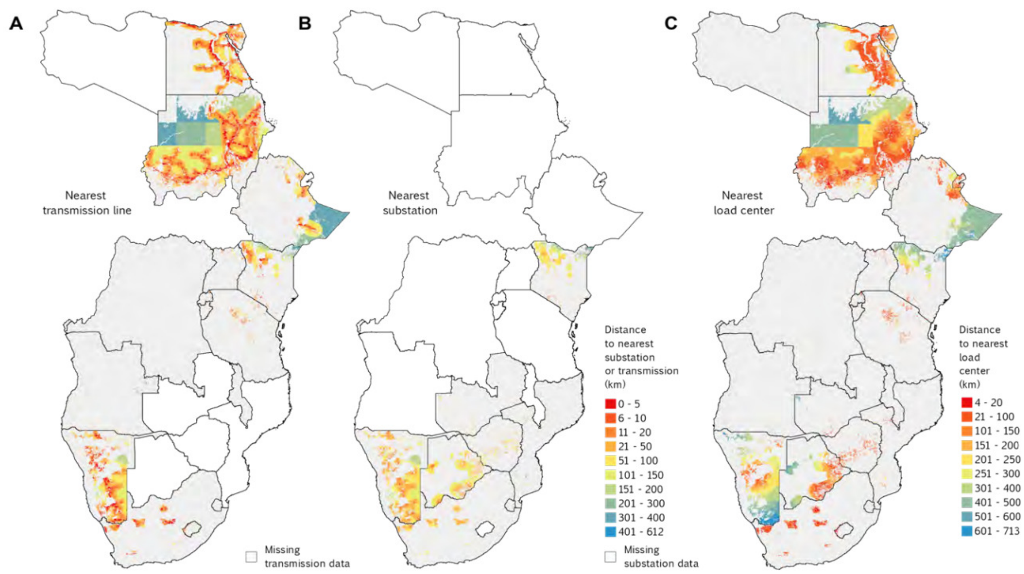
Successfully exploiting sub-Saharan Africa's renewable energy resources will demand whole-systems thinking. Although the region has abundant wind and solar resources, high-quality resources are unevenly distributed geographically, so promoting the supply of clean, low-cost wind and solar energy to all countries will require effective regional collaboration and grid interconnection (Wu et al., 2016). Differences in the operational characteristics of various generation technologies can be complementary, thereby reducing the need for one-for-one backup generation and storage for renewables. For example, increased wind and solar capacity in countries like South Africa and Tanzania can be used along with existing hydropower generation in countries such as DRC, Ethiopia, Malawi, Mozambique, Uganda, and Zambia to provide balancing services to regional grids. At the same time, solar and wind generation may reduce the risk of inter-annual and climate-driven variation in hydropower availability. Many of the high-potential renewable zones are close to existing transmission infrastructure and major load centers, thus requiring lower transmission upgrade and extension costs (Figures 6 and 7). These synergies can be exploited. Dual land-use strategies, such as the combination of agricultural land and wind development, will prevent potential conflicts that come with land access. Wind and solar generation sites can be co-located in order to reduce costs, maximize transmission efficiencies, and minimize ecological impacts (Wu et al., 2016).

Figure 6: Distance of high–wind energy zones to nearest transmission (A), substation (B), and load center (C) in Eastern and Southern Africa



Source: Wu et al., 2015.

Figure 7: Distance of high–solar energy zones to nearest transmission (A), substation (B), and load center (C) in Eastern and Southern Africa



Source: Wu et al., 2015.

3. ELECTRICITY DEMAND IN SUB-SAHARAN AFRICA

Data on demand for electricity in sub-Saharan Africa are often unreliable or unavailable, but the data that are available show that demand growing quickly and a large portion remains latent due to low access levels in the region.

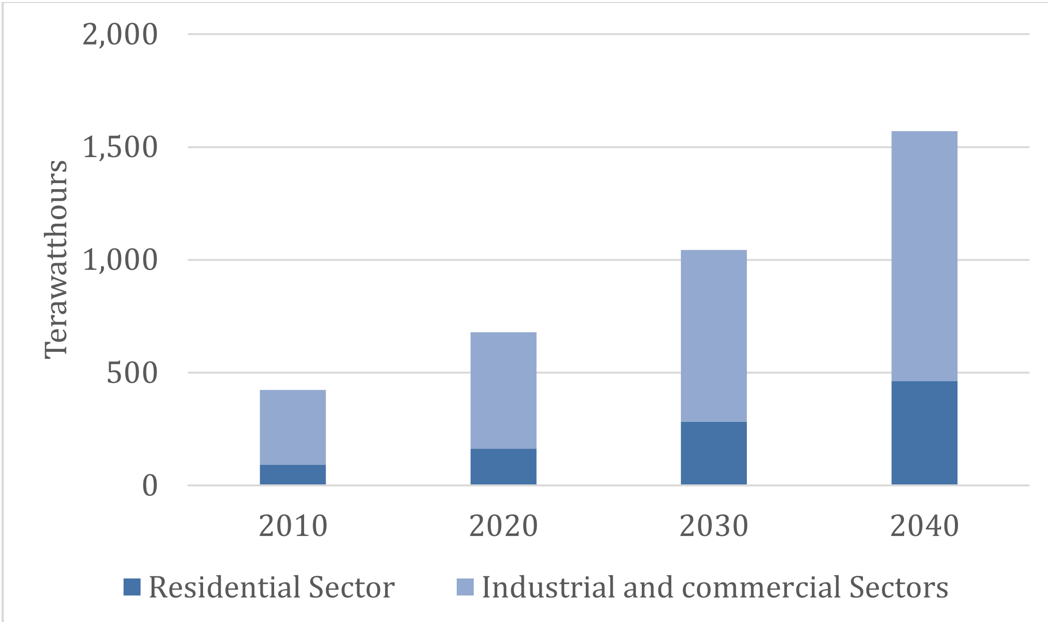
DEMAND ESTIMATES AND PROJECTIONS

The International Energy Agency (IEA) estimates that electricity demand in the region grew by about 35% from 2000 to 2012 to reach 352 TWh. Currently, average per capita electricity consumption in sub-Saharan Africa is 488 kWh a year, the lowest rate of any major world region. By comparison, in North Africa, where the electricity access rate is over 90%, electricity demand increased by more than 80% from 2000 to 2012 reaching 1,500 kWh per capita. The greatest demand in sub-Saharan Africa is in Nigeria and South Africa, which together account for about 40% of total demand (IEA, 2014).

The IEA forecasts that total demand for electricity in Africa will increase at an average rate of 4% a year through 2040 to reach 1,570 TWh, including captive power estimates (Figure 8). McKinsey's power sector report on sub-Saharan Africa estimates electricity demand at 423 TWh in 2010 and also projects an annual growth rate of about 4% through 2040 (Castellano et al., 2015).

Discrepancies in estimates of historical electricity demand, particularly owing to unreliable data on captive power and self-generation, add to the uncertainty of demand projections, which are so important in deciding the future design of the region's power system. This is why the open source modeling tool in section 8 has been designed to estimate power system capacity expansion pathways despite poor data availability and access.

Figure 8: Expected growth in electricity demand in sub-Saharan Africa



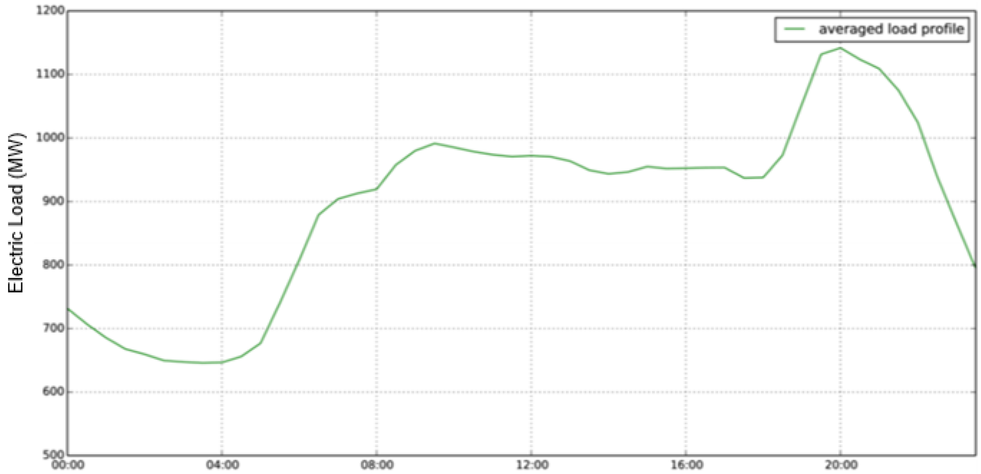
Source: Castellano et al., 2015.

FUTURE DEMAND PROFILES

As African countries develop, their electricity demand profiles will change. Current demand profiles show that in most of Africa, demand for electricity peaks in the evening. The shape of this demand profile—particularly the size of peak demand relative to average demand—is important for capacity planning. If peak demand is much greater than average demand, more generation capacity will have to be installed, even if that capacity is used for only a few hours a day when peak demand occurs. The need for "peaker plants" greatly impacts the economics of the grid.

Not only the size but also the timing of peak demand is important because of the hourly availability of variable renewable resources. Peak demand in Kenya, for example, and other counties in sub-Saharan Africa occurs in the evening (Figure 9). Solar power is not available in the evenings, so solar installed capacity will not contribute to the peak capacity required to meet demand. Solar, therefore, may be less favorable than other resources that can be available during all hours of the day. This is why storage technologies play a major role in deploying renewable energy. Batteries can, for example, store solar energy during peak production times in the afternoon and discharge it in the evening during peak demand hours.

Figure 9: Average weekday load profile of the Kenyan power system in 2012



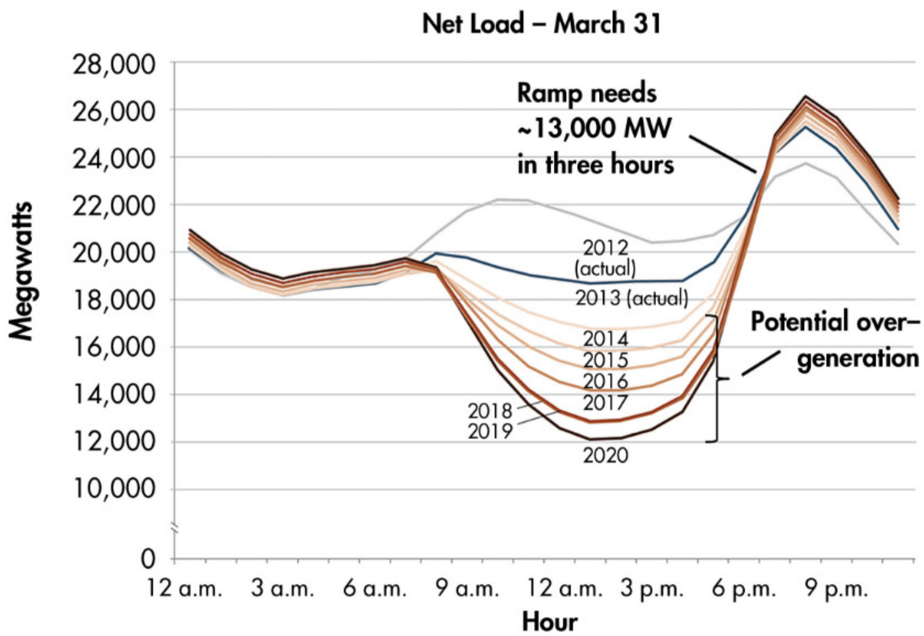
Source: Ackermann et al., 2014.

As the manufacturing and service sectors develop in the region and the shape of the demand profile evolves, peak demand hours may shift to earlier in the day, during peak solar production. Such a shift would greatly improve the grid value of solar energy and make it more optimal in system planning.

The U.S. state of California has a power system that integrates large amounts of non-dispatchable energy; its experience thus suggests some of the challenges sub-Saharan Africa may face in integrating solar PV and wind. The duck chart shown in **Figure *10*** shows the net load of the California electricity grid over a day. Each line represents the net load, equal to the normal load minus wind and PV generation. The "belly" of the duck curve represents the period of lowest net load: the afternoon, when PV generation is at a maximum. The belly of the curve grows as PV installations are projected to increase between 2012 and 2020. As the sun sets in the evening and solar generation falls, the net load increases. This results in steep ramps in output from other dispatchable generators, usually thermal plants.

The duck chart shows how solar PV could potentially generate more electricity than the grid can consume. During overgeneration conditions, the supply of power exceeds demand and requires flexibility, such as demand response, grid storage, or, ultimately, a reduction in output from conventional generation plants. When conventional generation cannot be backed down any further to accommodate the oversupply of variable generation, it leads to curtailment. Curtailment occurs when a system operator decreases the electricity output from a wind or PV plant below what it would normally produce. For wind generators, this is performed by changing the blade angle. For solar plants, generation is curtailed by either reducing output from its inverter or disconnecting the plant altogether. Curtailment raises several challenges. It requires a system operator to have physical control of the generator, which is typically the case for large renewable power plants but not for smaller systems, particularly distributed or rooftop systems. Curtailment also reduces the economic and environmental benefits of solar and wind plants because each unit of curtailed energy represents a unit of energy unsold and a unit of fossil fuel generation not displaced. As the amount of curtailment increases, the overall benefits of additional solar may drop to the point where additional installations are not worth the cost (Denholm et al., 2015). This is why grid flexibility is critical to sub-Saharan Africa's transition to a low-carbon grid.

Figure 10: Changes in the net load on the California grid at high rates of renewable penetration

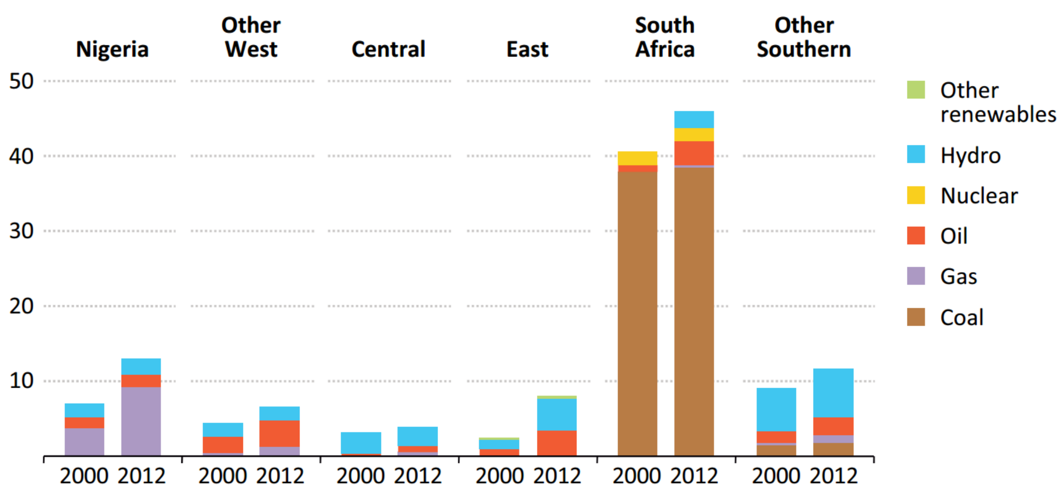


Source: Denholm et al., 2015.

4. ELECTRICITY GENERATION

Sub-Saharan Africa's power grid has an installed generation capacity of about 90 GW—about 0.1 kW per capita, in stark contrast with wealthier economies that have installed capacities ranging from 1 to 3 kW per capita (IEA, 2014). Half of the region's capacity is located in South Africa, and 13 GW are located in Nigeria (Figure 11). Only about 6 GW (or 40%) is operational owing to poor maintenance and fuel shortages in Nigeria. The installed capacity for many sub-Saharan African countries is less than 1 GW (IEA, 2014). Excluding South Africa, the entire installed generation capacity of sub-Saharan Africa is only 28 GW, equivalent to that of Argentina (Castellano et al., 2015).

Figure 11: Installed grid-based capacity (GW) in sub-Saharan Africa, 2000 and 2012



Source: IEA, 2014.

The region's dearth of generation capacity is partly due to its low level of investment in power systems, which currently accounts for about 0.5% of its gross domestic product (GDP) (Africa Progress Panel, 2015). According to a recent report, sub-Saharan Africa has the potential to install about 1 terawatt (TW) of generation capacity from a range of different technology options, excluding solar (Castellano et al., 2015). About 20% of the region's current generation is from hydropower and more than 70% is from fossil fuels (Cartwright, 2015). This dependence on fossil fuels is at odds with resource potential estimates that show the abundance of renewable resources in the region.

The installed utility-scale generation capacity and mix of each region is as follows:

- **Southern Africa** has more installed grid generation capacity than the rest of sub-Saharan Africa. Of Southern Africa's total 58 GW, 80% is in South Africa alone. The rest of Southern Africa has only 12 GW, mostly hydropower with some coal, oil, and gas. South Africa gets 85% of its generation capacity from coal and the rest from oil distillate (6%), hydropower (5%), and nuclear (4%). It is the only African country with nuclear power plants (with a capacity of about 2 GW). In 2012, the average cost of grid generation across Southern Africa was about $55 per MWh, owing to the high use of low-cost coal and hydropower (IEA, 2014).

- **West Africa's** grid generation capacity is estimated at about 20 GW. Of this capacity, more than 50% is gas generation (mostly in Nigeria), about 30% is oil distillate, and about 20% is hydropower. Some countries, like Benin, Burkina Faso, and Niger, import most of their electricity. In 2012, the average cost of generation was about $140 per MWh, owing to dependence on gas and oil generation (IEA, 2014).

- **East Africa** has grid generation capacity of about 8 GW, of which 50% comes from hydropower, 45% from oil distillate, and the rest from geothermal and gas. About 250 MW of geothermal resources lie mainly in Kenya. In 2012, the average cost of generation was $110 per MWh, despite the region's inexpensive hydropower generation, owing to the high use of expensive oil generation plants (IEA, 2014).

- **Central Africa** has the lowest grid generation capacity in sub-Saharan Africa, at 4 GW, composed mainly of 65% hydropower, 15% gas, and 20% oil distillate. In 2012, the average cost of generation was around $95 per MWh, owing to the low cost of hydropower (IEA, 2014).

INDEPENDENT POWER PRODUCERS

Electric utilities in sub-Saharan Africa are typically vertically integrated—that is, they control all levels of the supply chain: generation, transmission, and distribution. Because of the poor performance of the power sector in the region, however, many countries have attempted to unbundle their electricity utilities to allow participation by independent power producers (IPPs). IPPs are entities, usually private, that generate and sell electricity to utilities and end users. Ghana, Nigeria, and Uganda have had some success in this area. Nonetheless, as of 2014, 21 countries in the region still had state-owned and vertically integrated utilities with no private sector participation, precluding IPPs. Some countries remained vertically integrated but still introduced IPPs.

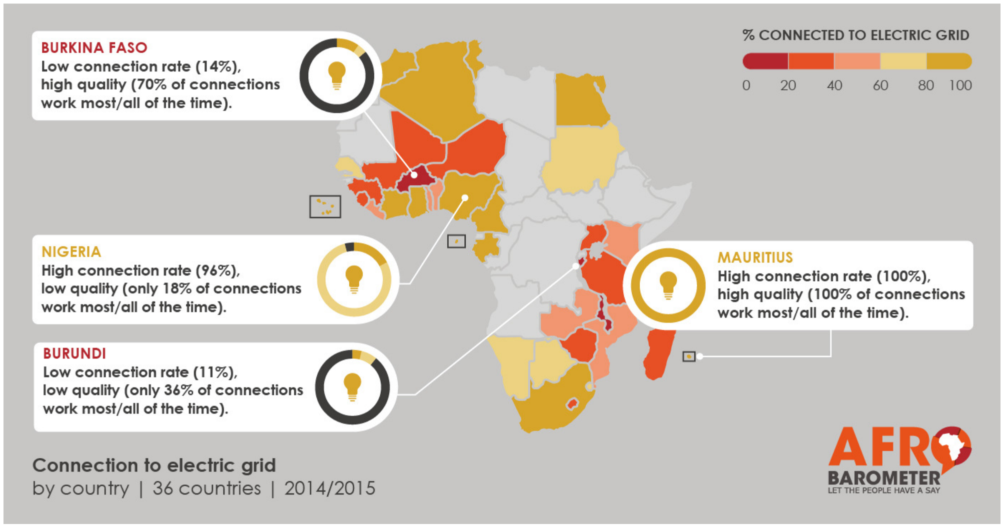
Currently 18 sub-Saharan countries have IPPs, with a cumulative capacity of 6.8 GW. These IPPs range in size from a few megawatts to 600 MW. The overwhelming majority of IPP capacity (82%) is thermal; 18% is fueled by renewables. The presence of IPPs can help reduce the perception of risk in investing in power systems in the region and encourage private investment. To succeed, IPPs require favorable local investment climates, clear policy and regulatory frameworks, local availability of cost-competitive fuels, and effective planning, procurement, and contracting practices (Eberhard et al., 2016).

SELF-GENERATION

Installed capacity estimates in the region are appallingly low compared with the resource potential, and the situation is even worse than those estimates indicate. Installed capacity and grid presence does not guarantee that people have access to electricity. In Nigeria, for example, abundant fossil energy potential and the development of petroleum-producing infrastructure have not increased reliable connection to the electric grid (Figure 12).

Sub-Saharan Africa's inability to provide reliable electricity has led to the prolific growth of inefficient and expensive on-site self-generation by industrial, commercial, and even residential consumers, reaching up 10% of the region's generation capacity. This has increased the cost and risk of doing business in sub-Saharan Africa. Lack of reliable electricity has resulted in economic losses of about 2% of the region's GDP and about 5% of annual sales of its firms (Castellano et al., 2015). In Nigeria, 85% of firms use a back-up generator (Cartwright, 2015). These back-up generators are expensive, costing about 300% more than electricity from the grid (Foster & Steinbuks, 2009). This prolific use shows the region's appetite for electricity and willingness to pay for it.

Figure 12: Connection rates and connection quality in African countries



Source: Afrobarometer, 2016.

Text Box 2: The dangers of onsite generators

On-site generators are usually noisy, pollute the living and working environments of communities, and pose significant risks of fire and respiratory illnesses. Energy poverty, both for primary uses such as cooking and for electricity, creates significant health threats. About 600,000 premature deaths in Africa can be attributed to household air pollution from the burning of solid fuels for cooking, while household diesel generators increase the risk of carbon monoxide poisoning and fires.

CURRENT CHALLENGES

The electricity sector in the region presents a unique set of challenges. While sub-Saharan Africa contributes the least of any global region to greenhouse gas emissions, it is most vulnerable to climate change impacts such as droughts and reduced agricultural yields (Kang et al., 2009). Erratic rainfall patterns and prolonged droughts can reduce hydroelectric output and force extended outages (Foster & Steinbuks, 2009). The following challenges are priority targets for reform in sub-Saharan Africa's electricity sector, with the aim of reaching affordable energy access and sustainability goals across the region.

- **Lack of system capacity.** The region's persistent electricity scarcity has crippled economic growth and prevented it from attaining several of its health and education development goals (IEA, 2014). Causes of this scarcity include lack of generation capacity for grid-connected regions, absence of proper grid infrastructure to deliver generated power, poor maintenance of generation plants, regulatory challenges that prevent a steady flow of revenue to maintain and invest in new generation capacity, and the dispersal of population in remote areas. This lack of systematic planning for the power sector has resulted in a system with high transmission and distribution losses (averaging 18% across the region when South Africa is excluded) (IEA, 2014), and created a high dependence on large dams and expensive diesel plants.

- **Poor sector management.** Reforming the energy utilities and their regulation to improve their operational efficiency and promote regional cooperation is key to closing the electricity gap. The region spends billions of dollars on utility losses and petroleum subsidies, which do not benefit power sector development (Africa Progress Panel, 2015). Since most utilities cannot recover their costs without these subsidies, power systems development is perceived as high risk and is thus unattractive to private investors. Therefore, most energy investments are limited to energy commodities produced for export, for which prices can be better guaranteed.

- **High system losses.** System losses in sub-Saharan Africa are double the world average. They include technical losses from poorly maintained transmission and distribution networks, and commercial losses from low revenue collection. Transmission and distribution losses are estimated at 18% across the region, when South Africa is excluded (IEA, 2014). These losses increase the generation capacity that is required to meet load, making centralized generation uneconomical, exposing power companies to large financial risks, and increasing end-user tariffs (Castellano et al., 2015).

- **Dependence on large dams.** Because of the seasonal variability of hydropower output and the impact of prolonged droughts in the region, reliance on large dams creates fragile power systems and increases the financial and climate risks in the region (Kammen et al., 2015). Until now, the environmental and financial risks of large dams have largely been evaluated while the dams are in operation, but a recent Oxford study shows that in most cases, even without accounting for negative externalities on the environment, the construction costs of large dams are too high to yield positive returns on investment. This is mostly due to cost overruns and implementation delays (Ansar et al., 2014). The study has shed new light on long-term energy strategies and debunked the notion that dams produce cheap power. For example, Kariba Dam, which holds the world's largest reservoir and accounts for 40% of Southern Africa's generation capacity, has been incapacitated by ongoing droughts exacerbated by climate change. The dam, which sits on the Zambezi River Basin, is at high risk from weather extremes, both floods and droughts. Given that the dam supplies half of Zambia's electricity, this vulnerability threatens the country's economic activities (Leslie, 2016).

- **Dependence on fossil fuels.** Fossil fuels pose a range of challenges. The region has abundant natural gas reserves that are threatened by mismanagement and systemic venting and flaring. Expanding gas infrastructure to provide electricity will require careful management to prevent methane leaks—this will be one of the biggest challenges of mitigating climate change while providing electricity. The prolific use of coal in Southern Africa has electrified the region but burdened it with significant air pollution and public health challenges. Countries that depend heavily on the oil industry, such as Nigeria, are affected by price changes in the international market. The sharp fall in oil prices between July 2014 and January 2015 resulted in a 28% drop in Nigeria's revenue (IRENA, 2015).

One way of overcoming the sector's challenges is through regional power pools that allow countries to aggregate resources and extend grids across national borders to capitalize on regional diversity in resources and demand. Four regional power pools already exist, but only about 7% of electricity is traded across international borders, mostly through the South African Power Pool. Facilitating increased use of the region's four power pools could save over $50 billion in capital investments in the power sector (Castellano et al., 2015). Other strategies to incorporate large amount of variable renewable generation include using existing reservoir hydropower to provide storage, deploying novel chemical and mechanical storage technologies, and adopting widespread demand response programs.

5. SOLUTIONS TO THE ELECTRICITY GAP

Closing sub-Saharan Africa's electricity gap has two main components. One component involves increasing the region's electricity supply and determining whether new generation capacity will come from fossil or renewable sources. The second component involves meeting electricity demand and determining the role of centralized and decentralized grids in increasing people's access. These two components are intertwined and can be made complementary using strategic frameworks and policies.

THE FOSSIL FUEL PATH TO INCREASING SUPPLY

The main challenges of using fossil fuels to increase the supply of electricity are price volatility and variability, local pollution, and climate change.

First, the volatility and variability of fossil fuel prices create a multifaceted problem: importing countries face an insecure fuel supply, while price variability causes oil and gas producers to curtail supply under low oil and gas prices and generators to suffer high economic losses under high oil and gas prices. The uncertainty affects the economics of energy systems, and with most countries locked into their fuel choices for decades, it increases the risk of stranded assets whose operating costs are no longer affordable (African Development Bank, 2013).

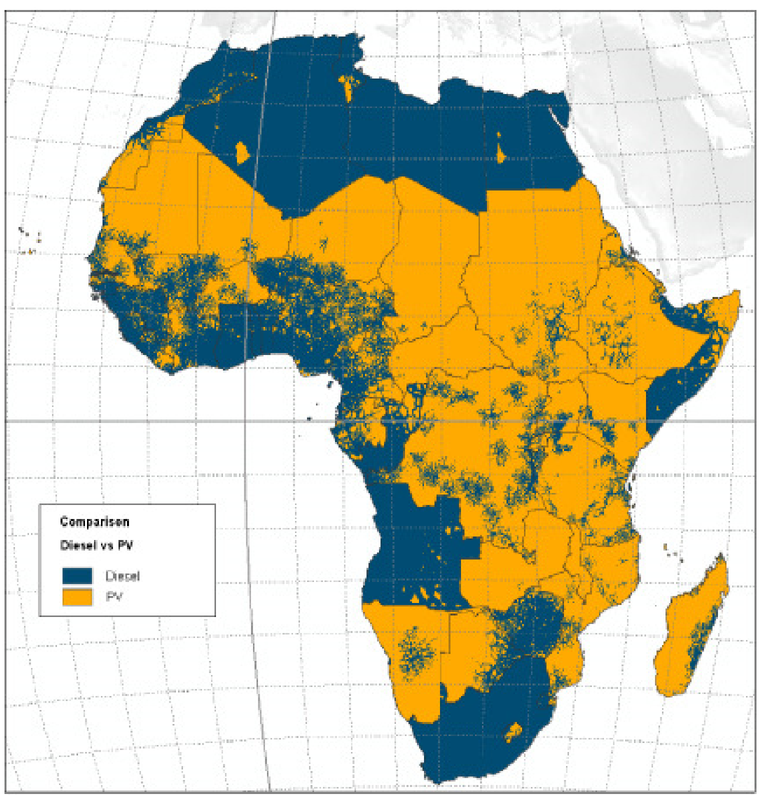
Text Box 3: Unstable supply in Nigeria

70% of Nigeria's fleet of power plants rely on natural gas. Insecure and unreliable natural gas supply incapacitates Nigeria's generation fleet, increasing the use of private diesel generators as backup. In 2012, more than 10 TWh of Nigeria's electricity demand was met by backup generators (IEA, 2014).

Second, the prevalence of subsidies in sub-Saharan Africa creates a significant barrier to moving away from fossil fuels. Governments spend about US$21 billion a year on fuel subsidies, including subsidies covering utility losses (Africa Progress Panel, 2015). The vast majority of these subsidies are spent in North Africa, as well as in Angola and Nigeria. By straining national budgets and discouraging investment in renewable resources, the subsidies inhibit sustainable energy development. They will eventually trap the region's energy investments in carbon-intensive technologies that could become stranded assets in the event of future climate and emissions regulations. Several sub-Saharan countries such as Angola, Ghana, Kenya, Nigeria, and Uganda have tried to reform their policies in recent years. In particular, Kenya successfully reformed its electricity fuel cost subsidy by allowing an automatic pass-through of changes in fuel cost to aid the development of domestic renewable energy (Whitley and van der Burg, 2015). To close the electricity gap sustainably and cleanly, some of these investments in fossil fuel subsidies may have to be channeled to renewable energy systems.

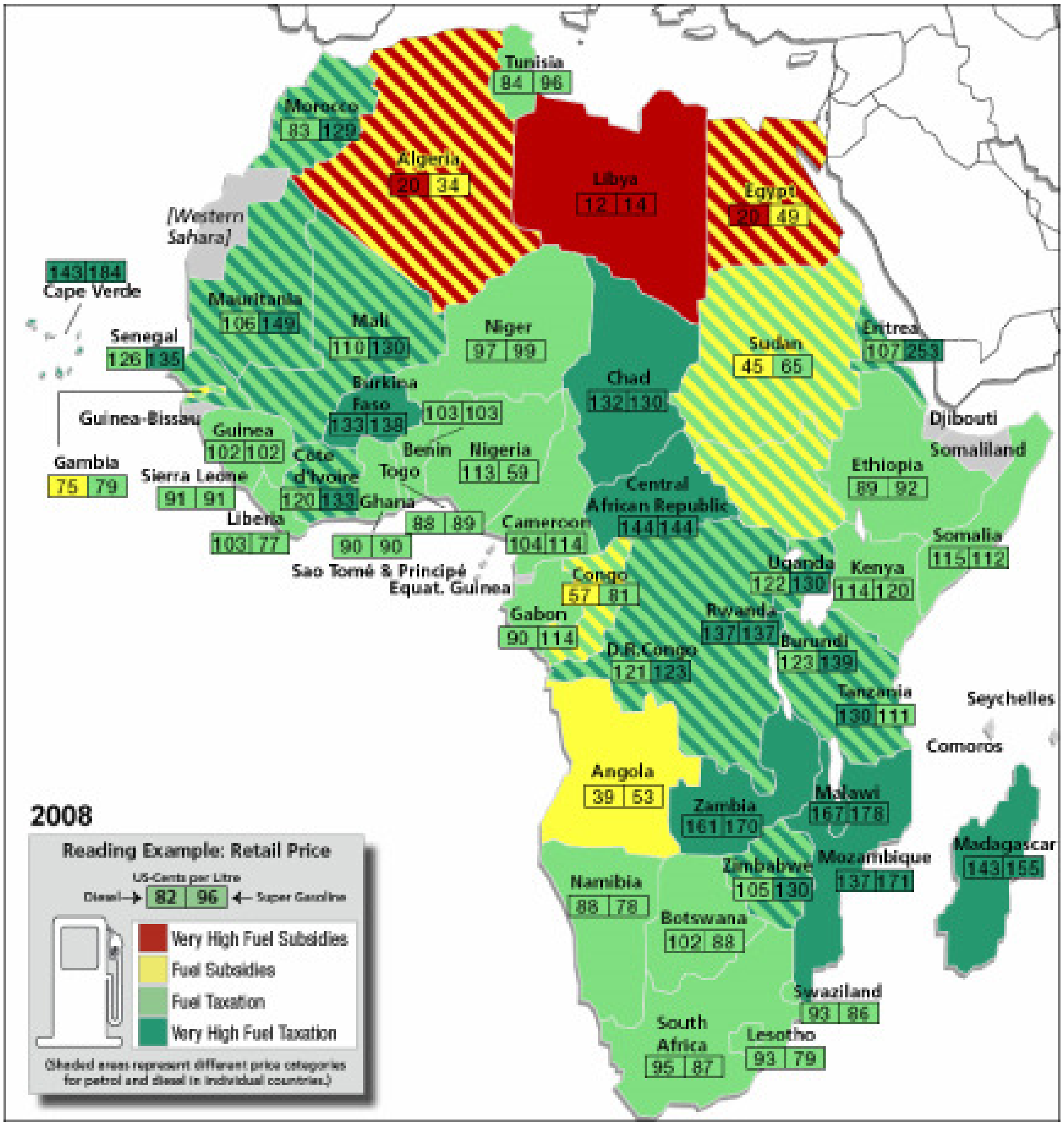
A study of cost-optimal rural electrification options in Africa demonstrates the impact of subsidies on electricity access. The study compared diesel generators, solar PV, and grid extension options for off-grid areas and found that the presence of subsidies was crucial in determining if solar PV was cost-optimal compared with diesel. Neighboring countries (with similar geographical factors) had different optimal choices (Figure 13), revealing how sensitive rural electrification costs are to fuel prices. The subsidies that exist for diesel, as shown in **Figure *14***, could also be directed toward supporting PV to avoid distorting the emerging rural electrification market (Szabo et al., 2011).

Figure 13: Optimal option for off-grid electrification in Africa, comparing diesel with solar PV



Source: Szabo et al., 2011.

Figure 14: Retail fuel prices in Africa in 2008, illustrating regions with high fuel subsides and taxes



Source: Szabo et al., 2011.

Finally, pollution from coal-fired plants will have significant impacts on local public health and climate change. Urban areas in sub-Saharan Africa already suffer from high levels of air pollution owing to the prolific use of diesel generators in residential and commercial buildings. South Africa's Mpumalanga province, which is home to 12 coal-fired power plants, has among the world's highest levels of air pollution, particularly nitrogen dioxide, particulate matter, and sulfur dioxide. Emissions there exceed the maximum level recommended by the World Health Organization (Siegfried, 2014).

The role of carbon capture and storage

Some of the environmental challenges associated with a fossil fuel path could be alleviated by carbon capture and storage (CCS) technologies, which prevent large amounts of CO_2 from being released into the atmosphere. These technologies capture CO_2 produced by large industrial power plants, compress it for transportation, and then inject it deep into a rock formation at a carefully selected safe site, where it is permanently stored (Global CCS Institute, n.d.). Ten countries, including Canada, China, Malawi, and Saudi Arabia, made CCS part of their climate commitments at the Paris climate conference. CCS is viewed as a bridge technology that would buy time to make the transition to a sustainable economy based on energy conservation and renewable energy sources (Vergragt et al., 2011). It will require significant investment in new infrastructure such as pipelines and long-term monitoring.

Using CCS as a bridge technology to transition to low-carbon systems could, however, lock in fossil fuel use, particularly in sub-Saharan Africa, where much of the needed generation capacity has yet to be developed. Combining CCS with bioenergy production, in an approach known as BECCS, could alleviate this risk. BECCS involves sustainably producing biomass, using it to generate electricity, and sequestering its emissions—the result is an effective carbon sink.

There are several barriers to deploying CCS in sub-Saharan Africa, including the high capital cost, the risk of carbon leakage, and the region’s limited geologically feasible sites and lack of regulatory frameworks. CCS could also threaten food security in countries where the geologic potential for carbon storage is found on fertile agricultural land (Román, 2011).

THE RENEWABLE PATH TO INCREASING SUPPLY

The main challenges of using renewables to expand the supply of electricity are the risk that climate change will hamper hydropower, the intermittency and variability of solar and wind, and the risk of overgeneration and curtailment.

First, while sub-Saharan Africa has the potential to generate abundant clean, renewable, and affordable electricity through hydropower, a number of studies (such as Kammen et al., 2015) reveal a high risk that climate change will reduce the performance of hydropower dams, as seen recently in the Kariba Dam. Droughts and unprecedented variability in rainfall will constrain the technical performance of large hydropower reservoirs, with long-term impacts on agriculture and electricity production (Kang et al., 2009). Large dams pose social and ecological risks as well. They can threaten livelihoods by causing the loss of agricultural land and requiring community resettlement. Dammed reservoirs can result in stagnant reservoir water, high sedimentation, and algae growth that impact wildlife (Union of Concerned Scientists, 2016). For example, the development of the Akosombo Dam on the Volta River in Ghana led to the resettlement of about 80,000 people from 740 villages. It also resulted in biodiversity loss and floods that increased the risk of water-borne diseases (Kalitsi, 2003). There are measures that can alleviate the detrimental impacts of large dams, and implementing them requires effective policies and management.

Second, renewable sources of generation, such as wind and solar are variable and intermittent—that is, they are available only when the wind is blowing and the sun is shining. Still, they can be forecast to some level of certainty. The real challenge is that grid systems are conventionally designed to rely on controllable generators rather than intermittent sources. Many countries in sub-Saharan Africa may be able to leapfrog this challenge with intentional design.

Finally, electricity consumption in most countries in sub-Saharan Africa peaks in the evening, whereas solar generation typically peaks in the early to mid-afternoon. This mismatch raises a risk of producing more electricity than can be consumed (overgeneration) at certain times, when electricity generation would consequently be cut off and not paid for (curtailment).

Cost of renewables

The declining cost of renewables means that high economic cost is no longer the primary constraint to deploying renewables. The challenge is achieving effective grid operations. Globally, the weighted average cost of utility-scale installed solar PV dropped from about $5 per watt in 2009 to about $2 per watt in 2015. Costs in Africa have been comparable (Figure 15). Prices of solar PV modules have also dropped significantly since 2009, to about $0.52 to $0.72 per watt in 2015. In response to this cost reduction, Africa added about 800 MW of solar PV in 2014 and 750 MW in 2015, doubling its cumulative capacity (IRENA, 2016). Despite sub-Saharan Africa's high potential for solar generation, most of the continent's rapid solar capacity growth has been in North Africa. Recently, a proposed 800 MW solar plant in the United Arab Emirates reported an average cost of $0.03 per kWh (Clifford, 2016), compared with typical per kWh costs of $0.08 for large-scale hydropower, $0.10 for geothermal, and $0.07 to $0.14 for natural gas (IEA, 2014).

Figure 15: Installed cost of existing and proposed utility-scale solar PV in Africa, 2011–2018

Source: IRENA, 2016.Note: Each circle represents an individual power project.

Overall, attaining a 100% renewable vision in sub-Saharan Africa will require the following:

1. policies that incentivize renewable energy deployment and discourage new fossil fuel development,
2. innovative financing mechanisms that allow decentralized solutions to thrive and be integrated into future grid expansion,
3. an enabling framework that attracts private investors to the energy sector and builds human capacity by empowering local entrepreneurs,
4. improved organizational procedures and sector management that support operational power pools powered by international and interregional transmission lines, allowing power sharing and reduced costs,
5. policies that incentivize and support decentralized renewable energy systems that enable 100% access to affordable and reliable electricity, and
6. electricity supply strategies that prioritize diversity of resources such as dispatchable renewables and storage, negate the need for fossil fuels, and ensure supply security.

6. LOW-CARBON GRID OPERATIONS

The main challenge of a renewable-dominated capacity expansion pathway is not economic cost—it is the system flexibility required to cope with the intermittency and variability of solar and wind. High penetration of renewables requires a power system enabled with ICTs and other smart grid technologies that allow real-time system monitoring and remote control of voltage and power flow conditions, which are critical to the rapid response needed for the variability of wind and solar. It also requires effective grid management that uses power pools to enable long-reach regional cooperation and power sharing.

SYSTEM FLEXIBILITY

Power system infrastructure and managers must be able to adapt and respond to changing conditions in various time frames. Short-term grid flexibility involves balancing demand and supply over minutes and hours of a day, and long-term grid flexibility involves changing generation and transmission capacity over years of investment. Increasing the electric power system's flexibility is critical to reliable operation under high penetration levels of variable renewable resources. Sources of flexibility include dispatchable generators, increased transmission capacity and access, large balancing areas and regional cooperation, demand-side management, and storage.

Every power system possesses an inherent level of flexibility. Electricity cannot be "paused" as it flows on the wires in the grid, traveling from the generation source to various end-uses: it is impossible to temporarily store excess electricity on the wires of the grid in anticipation of a consumer's decision to flip a light switch. Instead, the amount of electricity being generated at any time needs to match the amount of electricity being consumed. Because demand can change rapidly (e.g., when people turn their lights on after dark), power systems are designed to be flexible in order to respond to such rapid changes—both predictable and unpredictable—in demand. Also, robust power systems should have enough extra generation capacity (also known as "operating" and "spinning" reserves[1]) to make up for unexpected generation failure (for example, when a power plant goes offline).

[1] See the lexicon in Text Box 1.

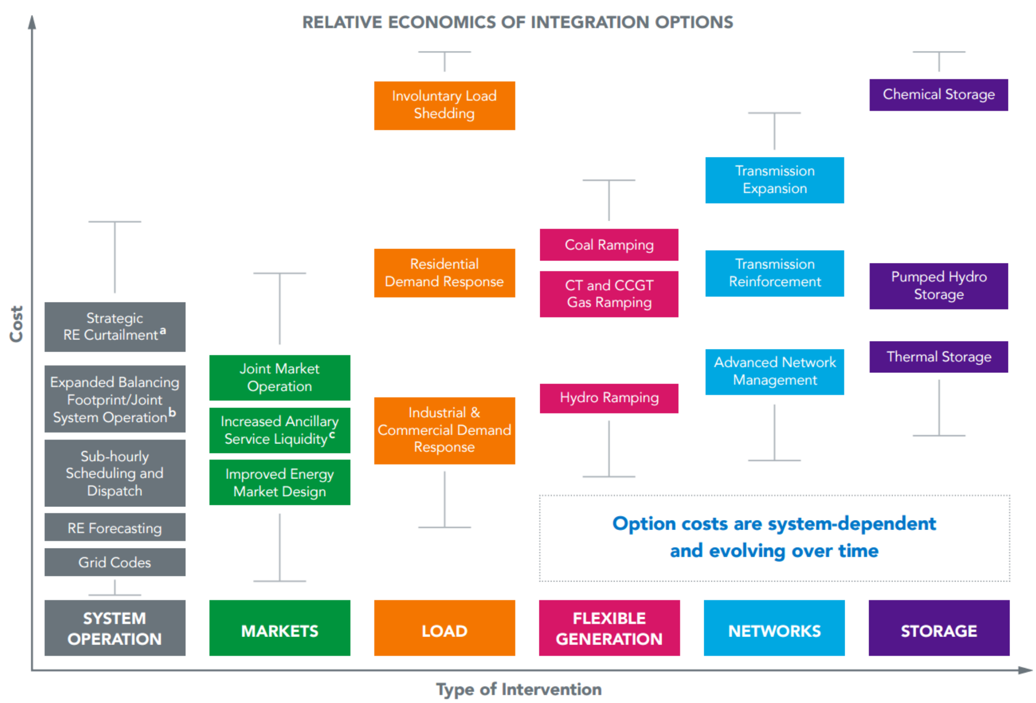
In general, power systems that rely heavily on natural gas and hydropower are more flexible than systems with large amounts of coal and nuclear. Coal and nuclear plants take longer to reach their full generation capacity (also known as their ramping time) than gas plants, and reservoir dams have storage capabilities. Conventionally, grid operators receive demand forecasts one day ahead that are updated in the hour ahead and finally in the minutes ahead of service. It is difficult to plan supply to match demand forecasts using solar and wind as they vary their output significantly over short time scales, such as hours (the wind can suddenly stop blowing over a large area, or the sun can go behind the clouds), and they are not dispatchable. Therefore transitioning to high penetration levels of variable renewable generation will require more flexibility. Backup generators can improve flexibility, and this backup capacity need not be at a one-to-one ratio; because the grid can act as a holistic system, each installation of renewable generation does not require an equal backup of dispatchable generation (Cochran et al., 2014). For example, an interconnected network of grids can supply electricity to cloudy areas drawing on solar generation in areas where the sun is still shining and using other dispatchable generation.

This potential of a holistic system argues for building effectively integrated power pools to link generation capacity over large geographical distances and smooth out the variable output of solar and wind. Because it takes several years to invest in and build new generators and transmission lines, planning for system flexibility is critical to ensure the growth of variable renewable generation. A highly flexible system ensures that renewables generators will not be curtailed (shut off) frequently, hence improving the capacity factor of renewable power stations and increasing the plant's electricity sales. These features improve the revenue streams and payback timelines, making renewable generators more attractive to investors and government stakeholders.

Figuring out how much flexibility is needed in sub-Saharan Africa is critical to informing policy-makers' investment decisions, particularly on fuel choices, in the upcoming years. This calculation requires in-depth power system modeling of each country's grid and the power pools (as task that is impossible for some countries with limited data access). Power system studies will dispel incorrect notions about the difficulty of operating power systems with high levels of variable renewable resources and make clear what the actual operating costs of renewable generation capacity will be. Some countries in the region have improved access to power system data, and in-depth studies have been carried out in Kenya and South Africa. High-resolution power system studies in Kenya have shown that the ratio of storage to wind capacity is about 1:10 for 30% penetration (Carvallo et al., forthcoming). This ratio is a proxy measure for how flexible the Kenya grid is to integrating renewables without storage. It also shows that variable generation like wind does not require one-to-one backup capacity to ensure a reliable supply (Carvallo et al., forthcoming). Besides adjusting supply side resources, power systems can improve flexibility by enabling demand response and using distributed storage.

In the transition to high renewable power systems, regulators and system operators can draw from a suite of options (**Figure *16***). The options include physical strategies such as battery storage, operational strategies such as ramping thermal fleets and improved forecasting, and institutional strategies such as new market designs and integration of demand response. Some sources of flexibility, such as pumped hydropower storage, are cheaper than adding grid batteries. Although options and associated costs to increase flexibility are system-specific, generally tools that help exploit existing flexibility through changes to system operations and market designs are cheaper than those that require investments in new sources of flexibility. Although changes to system operation and market design require less capital investment, they do have implementation costs and may entail changes to institutional relationships (Cochran et al., 2014).

Figure 16: Relative costs of strategies for increasing power system flexibility



Source: Cochran et al., 2014.

The first two columns of Figure 16—system operation and markets—represent low-cost options but require operational and organizational changes. The load column represents demand-side changes—particularly demand response. The remaining columns represent changes to the physical grid (generation plants and transmission networks).

High system flexibility will prevent the following operational challenges:

- **Electricity price volatility**. When generators are inflexible and cannot reduce their output during low load periods, excess energy on the system can cause prices to drop significantly, exposing plants to high financial risk. Also, when generators cannot increase their output during high demand periods, prices skyrocket, to the detriment of distribution companies and end users.

- **Energy curtailment**. Non-dispatchable or inflexible systems must be curtailed (shut off) during periods of high generation and low demand on the system.

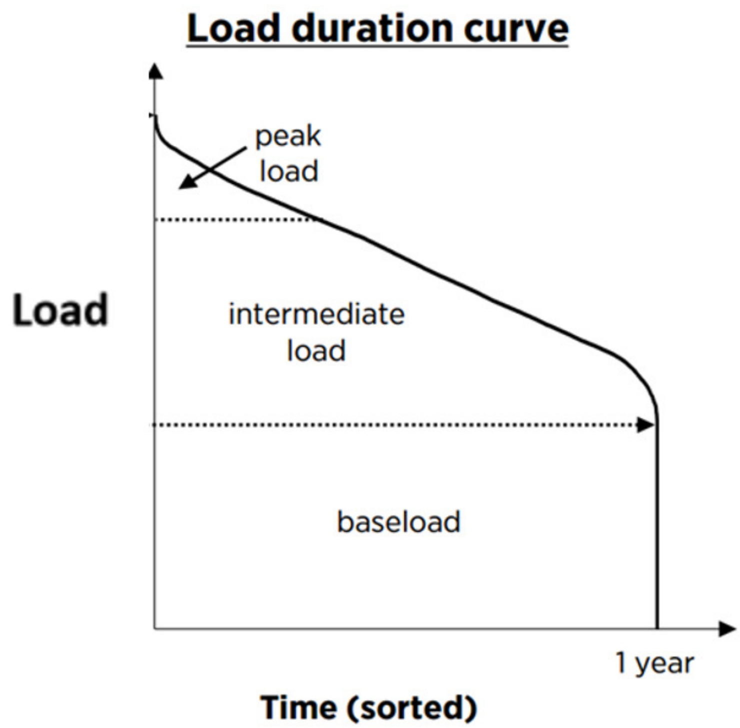
- **Load shedding/brownouts**. Quality of power to end-users depends on the power system frequency, which is kept at an optimal level by balancing supply and demand. Inflexible power systems necessitate brownouts and eventual load shedding in order to return balance to the system during periods of low generation and high demand.

Matching supply and demand across different load hours and regions (that is, across time and physical space) is critical to achieving system flexibility, which is why successful implementation of power pools in sub-Saharan Africa will facilitate high renewable energy deployment over the coming decades. Power pools aggregate loads and generators through transmission networks allowing for greater flexibility in supply and demand.

RENEWABLES AS BASELOAD CAPACITY

Electricity load is typically categorized as baseload, intermediate load, and peak load (Figure 17). Efforts to achieve high rates of renewable energy penetration face a challenge in reliably meeting baseload demand. Baseload demand refers to minimum or predictable demand in a power system that is not highly variable. Conventionally, baseload demand is met by nuclear and coal because these plants run at relatively constant output, have slow response times, and have high investment costs that need to be recovered quickly. Power systems with high penetrations of renewable energy require generation mixes with high flexibility, which in turn reduces the need for plants like nuclear, which have low flexibility. Non-dispatchable renewable generators such solar PV and wind cannot meet baseload at all times owing to their variability. However, dispatchable renewable generators such as large hydropower, biogas, and geothermal can supply flexibility to the power system and meet baseload demand. Therefore, the capacity of renewables to meet baseload demand will depend on the generation mix (of dispatchable and variable energy sources) and demand profile of the power system.

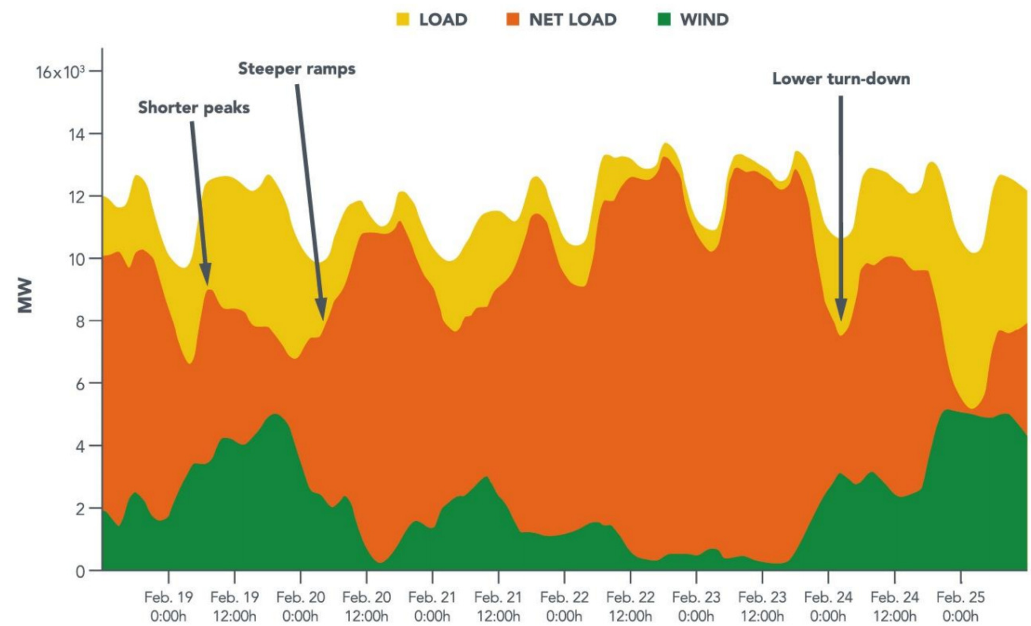
Figure 17: Load duration curve



Source: Ueckerdt and Kempener, 2015.

Renewable integration will increase as future power systems are enhanced with smart grid and information and communication technologies (ICTs) that allow greater remote control of centralized and distributed generation instead of requiring the system operator to have physical control of the generator. High system flexibility also helps manage high variability in generation—for example cloudiness over solar panels—that causes rapid changes in the net load (**Figure *18***). Rapid changes require fast-ramp plants that can respond quickly by increasing or decreasing generation in the form of peaker plants and spinning reserves. The amount of fast-ramp capacity required is dependent, then, on the power system's overall generation mix, the hourly load shape, the penetration of variable renewables, and the accuracy of demand forecasting. Since many parts of sub-Saharan Africa are not yet grid-connected, building a low-carbon grid with ICTs and storage technologies would not require large changes to existing infrastructure. Therefore, the region can develop intentionally by choosing strategic electricity supply mixes that enable high penetration of renewables. If the region chooses its future electricity supply mix with flexibility as a priority, it may reduce the need for centralized energy storage to manage high penetrations of renewables.

Figure 18: Net load of a grid system in the United States



Source: Cochran et al., 2014.

Demand-side management

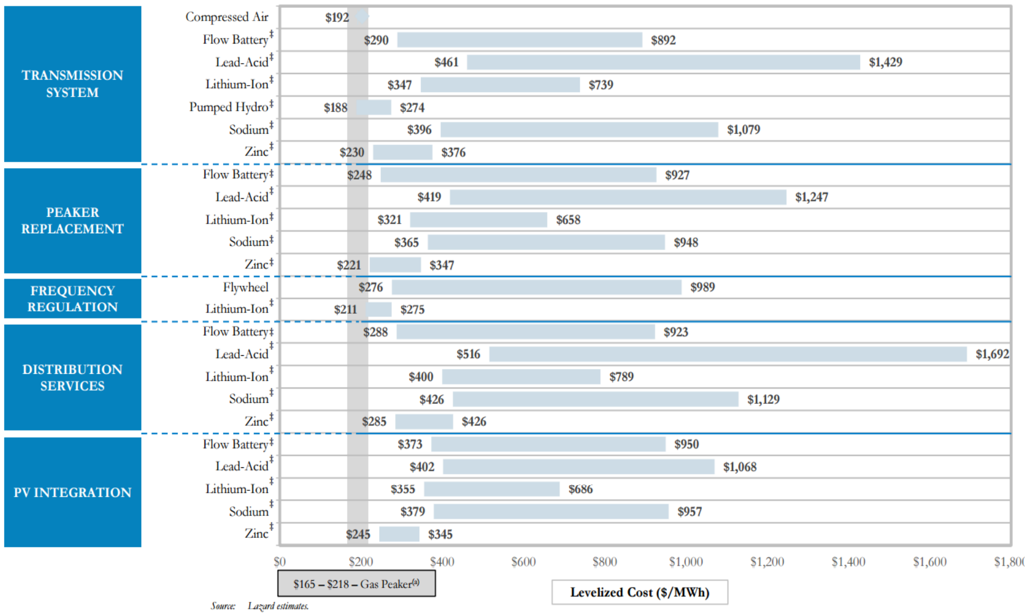
Energy efficiency will reduce the overall capacity required and the rate of load growth, enabling more sustainable and less expensive funding situations. Demand-side management strategies such as demand response can facilitate the use of renewables to serve a larger proportion of daily load and reduce the need for large-scale storage by reducing peak, and shifting demand to match the timing of variable generation. Demand response allows the shifting of loads by getting end-users to shut off appliances and larger industrial machines at peak times and to run those machines at specific off-peak hours instead, changing the load profile to match the generation supply. This is especially important for renewables as net load can change rapidly. It also allows demand to be met flexibly and quickly and avoids the curtailment of solar and wind generation.

Role of storage

The need for storage depends on how many flexible resources can be incorporated into the power system and on the shape of the demand profile. Inexpensive batteries will facilitate electrification through micro-grids until the centralized grid is extended to rural areas. Operational challenges due to the variability of wind and solar can be alleviated by forecasting solar insolation and wind speeds in order to plan electricity dispatch. In parallel, storage technologies that offset the variations in solar electricity output need to be developed. Batteries are not the only option, however. Sub-Saharan Africa could develop a diverse generation portfolio and use spinning reserves to manage intermittent generation from minutes to a few hours. Modern natural gas plants are designed to ramp up rapidly at about 50 MW per minute. These, combined with smart grid technologies such as improved sensing and control, will be sufficient to accommodate most of the intermittency problems of renewable energy without the need for additional storage. At very high penetrations of solar and wind, distributed energy storage sites may be needed. The most inexpensive ways to store electricity for the medium and long term are pumped hydroelectric and compressed air. These are greatly restricted, however, by geographical availability (Kenning, 2015). Apart from pumped hydropower storage using large reservoirs, the most prevalent type of storage in sub-Saharan Africa currently consists of batteries, mainly on the distributed scale for micro-grids. For example, in Marsabit, Kenya, flywheels are used to manage the variability of a micro-grid powered by wind and diesel (Kenning, 2015). Flywheel storage works by storing electricity in the form of rotational kinetic energy in a fast-rotating wheel. It spins faster to store energy and reduces its speed to discharge energy.

Overall, sub-Saharan Africa will require a mix of fast-ramp generation plants and energy storage technologies to support high penetrations of renewables with the least cost and environmental impact. Figure 19 shows the levelized cost of various energy storage technologies at different scales of implementation (Lazard, 2013), illustrating that a single technology can vary in levelized cost depending on what services it provides to the electric grid.

Figure 19: Unsubsidized levelized cost of energy storage across various technologies and grid service



Source: Lazard, 2013.

The future of nuclear power in sub-Saharan Africa

Nuclear energy, a low-carbon resource, could play a significant role in electrifying sub-Saharan Africa, and there is interest across the region in ramping up this form of generation. South Africa, the sole country in sub-Saharan Africa with active nuclear power plants, is seeking to expand its capacity. However, nuclear power has significant economic, environmental, and public safety risks. It has low operating costs and high fuel density but is burdened by high upfront capital costs. Nuclear plants are prone to long construction and licensing delays. Nuclear power raises safety concerns, including the issue of how to dispose of spent fuel and the risk of nuclear weapons proliferation accompanying the uptake of nuclear power technology and fuel enrichment processes. Its overall cost is about five times higher than the cost of natural gas generation. And the estimated cost of decommissioning each plant, including used fuel and site restoration costs is about $500 million (Chu & Majumdar, 2012). Small modular nuclear reactors could alleviate the challenge of cost and construction overruns, but the expertise and workforce required to safely adopt and operate nuclear plants are still lacking in the region (Castellano et al., 2015). As the cost of solar and wind decline and smart grid technologies including storage move forward, a nuclear pathway will expose the region to comparatively greater financial risk and energy insecurity (Chu & Majumdar, 2012).

POWER POOLS AS A FACILITATOR

Regional cooperation—fostered by power pools and cross-border transmission networks—will be critical to closing the electricity gap in sub-Saharan Africa. Such cooperation can offer economies of scale to small countries with limited load. It can reduce the average cost of generation by pooling countries' resources. It can help diversify countries' energy portfolios and shield them from price variability stemming from dependence on a single fuel or from hydropower seasonality. And it can reduce dependence on fossil fuel imports by enabling large concentrated renewable resources to be shared. For example, the benefits of geothermal resources in Kenya can be shared with South Africa, which is currently powered by coal, and hydropower in Central Africa can be shared with Senegal (Castellano et al., 2015), which is currently powered by diesel.

But regional cooperation poses its own political and economic challenges. To develop and operate power pools, member countries will need to find ways to effectively collaborate. They will need mutual trust in the power capacities of each country's grid system. They must train local personnel and develop power systems expertise. Finally, they must create effective international frameworks to govern both the legal and technical aspects of the interconnections.

There are four power pools in sub-Saharan Africa:

- **The Central Africa Power Pool,** created in 2003, consists of Angola, Burundi, Cameroon, Central African Republic, Chad, Congo, Democratic Republic of the Congo (DRC), Equatorial Guinea, Gabon, and Sao Tome. The CAPP is still in the development stage and is not yet operational.

- **The Eastern Africa Power Pool** (EAPP) was established in 2005 by seven countries: Burundi, DRC, Egypt, Ethiopia, Kenya, Rwanda, and Sudan. It has been adopted as a specialized institution to foster power system interconnectivity by the heads of state of the Common Market for Eastern and Southern Africa (COMESA). Since then, Libya, Tanzania, and Uganda have joined the EAPP. The EAPP has released master plans and regional power system studies and is projected to be fully operational within several years.

- **The Southern Africa Power Pool** was created in 1995 by 12 countries: Angola, Botswana, DRC, Lesotho, Malawi, Mozambique, Namibia, South Africa, Swaziland, Tanzania, Zambia, and Zimbabwe. It is the most advanced and active power pool in the region, with international energy trades and operational short-term energy markets.

- **The West African Power Pool** (WAPP) is a specialized institution of the Economic Community of West African States (ECOWAS) and consists of 14 countries: Benin, Burkina Faso, Côte d'Ivoire, The Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Niger, Nigeria, Senegal, Sierra Leone, and Togo. The WAPP is still under development and is not yet operational.

In 2012, the Programme for Infrastructure Development in Africa was initiated by the Africa Development Bank Group with a mandate to enhance cross-border energy market development, among other priorities. The program includes four electricity transmission corridors (not yet operational), three of which will be based in sub-Saharan Africa:

- a north-south transmission line from Egypt to South Africa with branches in East Africa,
- a transmission line from Angola to South Africa with branches in Central and West Africa, and
- a West African transmission line linking Senegal and Ghana with several branches in other countries.

7. DISTRIBUTED ENERGY RESOURCES

Expanding centralized generation capacity is not the only way to electrify sub-Saharan Africa. Off-grid and distributed energy systems now offer new opportunities to close the electricity gap. Historically, these off-grid systems were fueled by diesel, which presents a transport risk in remote areas. Now, owing to the modular nature of renewable energy such as solar and small-scale hydropower, most off-grid systems are powered renewably. Improved knowledge and management of electric distribution systems will facilitate distributed energy resources (DERs) such as rooftop and communal solar PV and battery systems.

THE POTENTIAL OF DISTRIBUTED ENERGY RESOURCES

DERs have many advantages over centralized grid systems, such as reduced power loss, scaled design, and suitability to renewable sources. In particular, DERs have the potential to alleviate the social inequalities reinforced by centralized grids. Existing grids in sub-Saharan Africa favor wealthier communities, which lie in areas where the limited grid exists and which can afford the relatively expensive connection fees, while rural communities are left with limited options for electricity access. This intraregional electricity gap perpetuates inequality by hindering the welfare development of those who are currently poor. DERs in the form of micro-grids have the potential to bypass this challenge and rapidly deliver power to communities without grid access.

Unlike transmission systems, distribution systems have in the past had little operator monitoring. With the advent of smart grid technologies, sub-Saharan Africa has the opportunity to make its grids receptive to DERs, taking pressure off of centralized generation and increasing overall grid reliability. ICTs will be critical to the success of DERs because they allow remote communication for maintenance and repair, easy data analytics, and smart metering. DERs are waiting on the right mix of catalysts, such as cheaper battery costs and smarter ICTs, to drive unprecedented growth and deployment.

So far, the discourse on electricity access in sub-Saharan Africa has been dominated by arguments that pit centralized solutions such as grid extension against decentralized solutions such as mini-grids. Some argue that mini-grids are incapable of supplying reliable and modern levels of energy services, while others argue that grid extension is too slow and expensive to reach the millions of people without electricity. These all-or-nothing arguments are based on the outdated assumption that electricity provision must come from large-scale centralized generation and grid networks commissioned by national governments. In reality, to outpace the region's growing rate of electricity poverty, both solutions must be deployed in tandem and synergistically (Casillas & Kammen, 2010). Micro-grids must be designed as a stopgap for main grid extension for several years, and they must be seamlessly integrated with the main grid when it arrives. Lack of integration may result in stranded energy assets, which will deter investors from investing in small private energy firms that may have the capacity to reach the remotest regions. Private micro-grid companies need to be supported by national electric utilities and rural electrification programs. Also, countries should build human capacity and enable job creation by giving workers access to skills training on installing and maintaining micro-grids. Finally, countries could also provide tax and import incentives to micro-grid developers.

COMPARISON OF DECENTRALIZED ENERGY TECHNOLOGIES

Strategies for deploying renewable electricity in off-grid areas include the use of solar lanterns, solar home systems, and solar micro-grids. To cope with intermittency, solar and wind micro-grids are often built as hybrid systems with natural gas, biogas, or diesel. As the cost of energy storage declines, renewable micro-grids can become the sole source of electricity in both grid and off-grid areas (for an in-depth comparison of these technologies, see Part 2 of this report).

Solar lanterns

Solar lanterns combine small photovoltaic panels with lighting fixtures. They are sold as a single unit or as a PV panel with a set of lights that can be charged during the day when the PV panel is generating electricity. In some parts of sub-Saharan Africa, standalone solar lanterns are readily accessible and can be found in supermarkets, hardware stores, gas station convenience stores, and other small vendors. Because of the declining cost of solar PV technology, solar lanterns can provide higher output and higher-quality lighting at the same or lower cost as kerosene lamps and candles, which would otherwise provide lighting. Because the fuel cost is zero, they also reduce the variable costs associated with kerosene and other common lighting energy sources.

Solar lighting trade associations, like the Global Off-Grid Lighting Association (GOGLA), and other organizations develop and enforce high quality standards to advocate for policies that foster a better business environment for solar companies. Despite these efforts, there are many inexpensive, poorly made solar lanterns that draw in consumers but reach the end of their product lifetimes over short periods of time, with few options for repair or maintenance.

Pico-solar and solar home systems

Pico-solar, or pico-PV, systems are very small solar PV systems that mainly supply power for lighting and other relatively low-load applications like phone charging. Capacities for pico-solar systems, as defined here, range from 1W to 10W. The cost of these systems, as well as larger-capacity solar home systems (SHSs), has dropped over the past decade thanks to major decreases in manufacturing and materials costs for PV panels. Solar technologies at various capacity levels have also become more cost-effective options for off-grid households owing to improvements in energy-efficient appliances and light bulbs, particularly light-emitting diode (LED) technology. They have also benefited from innovations in pricing and payment systems based on mobile phone banking transactions and other ICT advances.

In East Africa, companies like M-Kopa Solar are deploying pico-solar systems as a kit with several lighting and entertainment appliances. Consumers can purchase these either by paying the full cost upfront or by paying in installments over time using mobile money mechanisms such as M-PESA and Airtel MTN. This pay-as-you-go (PAYG) business model has boosted electricity access for communities without grid connections and without sufficient income to pay the capital costs of a home-scale solar system upfront. M-Kopa systems consist of 8W solar panels that come with several LED lights, a rechargeable radio, and a cell-phone charger. As of 2016, M-Kopa had connected more than 300,000 homes to solar power (PwC, 2016).

Companies marketing SHSs in emerging markets have, likewise, had success using the PAYG model combined with mobile phone payment systems, whether or not the systems are sold in tandem with appliances. Mobisol, a major supplier of solar home systems in Rwanda and Tanzania, bundles different ranges of solar PV panels (80W, 100W, 120W, and 200W arrays) with kits of direct-current (DC) appliances (see Figure 20). Its most basic package is an 80W system with seven LED lights, a mobile phone–charging station, and balance-of-system components, such as wiring and switches. This system can support lighting fixtures, charge multiple mobile phones, power a small radio, and run a television for several hours. Mobisol’s largest system provides enough power to charge laptops, run a DC refrigerator, and power a television for longer periods. Mobisol has to date installed more than 3 MW of solar home system capacity in East Africa—a testament to the PAYG business model and the appropriate product scale for low-income and rising middle-class customers without central grid access.

Figure 20: A sample 100W solar home system with kit of DC appliances from Mobisol

Source: Mobisol, 2017.

Micro-grids

A micro-grid is a small-scale power generation and distribution system that delivers electricity to multiple buildings in a village. Existing micro-grid projects in sub-Saharan Africa are typically privately owned and operated, with the initial capital for infrastructure investments coming from varied sources, including donors, private debt and equity investors, and government grants or loans. Micro-grids can also be owned and operated by a public utility or by a hybrid of private and public models.

Micro-grids can provide electricity to even remote sites because innovations in ICTs enable demand forecasting and pay-as-you-go services. Also, microgrids do not require large investments and long construction times—although the capital costs are still prohibitive for small and medium-sized entrepreneurs. Diesel fuel prices are variable, and diesel delivery to remote areas can add significantly to the transaction costs of electricity from a diesel generator. However, diesel is easily stored, and its generator technology is mature and standardized.

Renewable sources are now more affordable for use in micro-grids thanks to rapid renewable project construction timelines, falling prices of solar and wind technologies, and improving battery storage technologies. In addition, modern ICT systems allow for less-costly remote operation, billing and customer services, and mobile phone payment systems for customers in rural off-grid communities. However, tariffs for electricity from renewable micro-grids are usually higher than grid tariffs in urban areas because the micro-grids lack economies of scale and do not benefit from the government subsidies on grid tariffs.

Since renewable generation has no fuel cost, the decision to develop a diesel-based or a solar PV micro-grid lies in the lifetime cost comparison between the capital and fuel costs of the respective options. As capital costs for renewables decrease, especially in solar, renewable-based micro-grids are becoming more popular. Today, companies like PowerHive and PowerGen in Kenya are developing micro-grids that rely on solar PV generation, along with a few wind generation pilots, combined with battery storage, or hybrid renewable-diesel micro-grid systems (Figure 21). A hybrid diesel micro-grid with storage incorporated can supply electricity to consumers when wind speeds are too low to make power or after the sun sets each day.

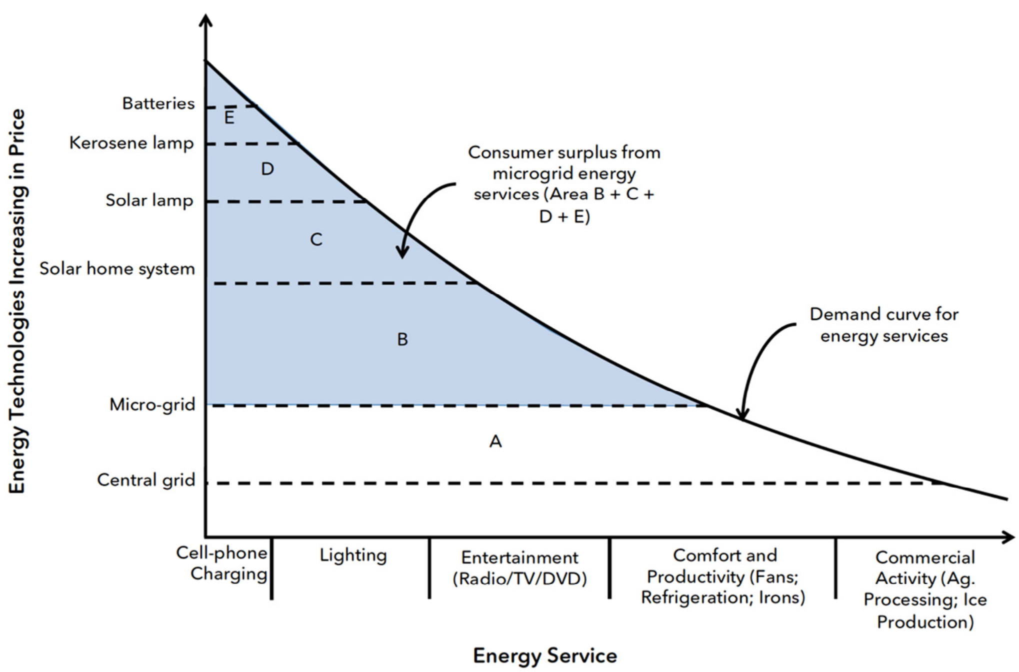
Figure 21: PowerGen project in Samburu County, Kenya showing a 3kW micro-grid

Source: PowerGen, 2017.

The main challenge facing micro-grids today is high regulatory uncertainty about the role and eventual fate of the physical assets if and when the central grid is built out and able to offer cheaper tariffs. Designing micro-grids to eventually connect to the central grid may reduce the uncertainty around micro-grid investments and change the nature of the energy services provided by the micro-grid. For example, a grid-connected micro-grid may evolve from an on-site generator into a power purchaser from the central grid, functioning as a small distributor of power to its existing household connections. To alleviate market uncertainty in the financing of micro-grid projects, a general regulatory framework for micro-grids could be put in place to clearly define how micro-grids can be licensed and managed. Policy changes of this nature may already be in motion in countries like Kenya.

The cost of electricity shapes the services people use and their demand for electricity. If electricity is expensive, households will use it only to access services that are highly valued, that require small amounts of energy, and that can only be provided by electricity (such as charging cell phones) or for which electricity does a better job of providing the service (such electric light versus candles). Likewise, households will refrain from using electricity for tasks that use large amounts of energy and for which substitute sources of energy might be available, such as cooking, which can be done using solid fuels. As prices fall, the number of services a household can access increases. As a result, the services any household is willing to access is related to the generation technology that determines the price of electricity. **Figure *22*** shows the relationship between the price per unit of energy to consumers and the energy services demanded for power from the centralized grid, a micro-grid, a solar home system, a solar lamp, a kerosene lamp, and batteries. In many parts of sub-Saharan Africa, the supply of electricity through the centralized grid can be unpredictable, with power shortages occurring in peak demand periods. Depending on the quality and consistency of service from the centralized grid, some customers may prefer to pay a premium for power produced by a reliable micro-grid rather than for unpredictable power from the centralized grid.

Figure 22: Per-unit energy price versus level-of-service chart for various energy technologies



Source: Schnitzer et al., 2014.

Achieving high penetration of renewables in sub-Saharan Africa presents challenges related to achieving system flexibility and gaining access to financing, but it also creates opportunities stemming from, for example, operational power pools and smart grid technologies that can lead to affordable clean electricity, reduced emissions, and less pollution. Policy-makers must consider all of these factors holistically to enable the development of a low-carbon grid.

8. CASE STUDIES OF CENTRALIZED CAPACITY EXPANSION

Vetting possible pathways to closing the electricity gap in sub-Saharan Africa will require modeling of the region's power systems. Existing analyses at the pan-African level estimate that capacity will grow annually at around 8–13%, expanding by 50–200 GW by 2025 (Bazilian et al., 2012; Sanoh et al., 2014; Sparrow et al., 2002). Yet modeling future power systems in sub-Saharan Africa will need to be context specific, varying from country to country, and there is little research in the literature on national-level sustainable power system expansion for individual countries. Power systems modeling of many countries in the region is challenging because of the lack of reliable and accurate data. Some countries, like Kenya, Nigeria, and South Africa (IRENA, 2015), have made considerable effort to record their power systems data, but even in these cases some data are not available in the public domain and access remains a challenge for researchers and analysts. Instead of a pan-continental model of all of sub-Saharan Africa based on unrealistic data, we attempt to illustrate the trade-offs of various capacity expansion pathways to closing the electricity gap through case studies of Kenya and Nigeria, where we have obtained reliable power systems data. The capacity expansion model[2] determines the least-cost pathway to expanding electricity generation over a time horizon (usually 20 years into the future) and compares the associated economic, environmental, and social impacts of these pathways.

Text Box 4: Modeling energy systems

This analysis focuses on quantifying the grid-based electricity supply needed to meet demand growth. The capacity expansion model determines the financially optimal generation portfolio for Kenya and Nigeria based on inputs such as the energy resource potential of the region, the existing installed capacity, average capacity factors, and peak contribution of each generation technology.

COUNTRY PROFILES

Kenya is chosen because it is one of the region's fastest-growing economies, with abundant renewable energy sources, yet only about 40% of its population

[2] See the model description in the Appendix.

has reliable electricity access. Nigeria is selected because it has the largest economy in Africa, with crippling electricity shortages in the midst of abundant renewable and fossil resources. Only about 50% of its population has reliable electricity access.

Kenya

Electricity in Kenya is distributed by the Kenya Power and Lighting Company (KLPC), which serves just over 2 million customers with a peak grid-based demand of around 1,250 MW. The installed generation capacity is about 2 GW: 44% hydroelectric, 36% fossil fuels (diesel and gas), 22% geothermal, and 0.3% wind power (Ackermann et al., 2014). Kenya is well positioned to integrate large amounts of renewables owing to its abundance of geothermal, wind, and hydropower, which are relatively cheap. It has rapidly added generation capacity over the past decade and made impressive progress in providing access to clean and affordable electricity. However, Kenya also had plans to add 4,500 MW of coal by 2030.

Nigeria

Nigeria is Africa's largest oil producer and in 2012 was the world's fourth largest exporter of liquefied natural gas. Nigeria's installed capacity is about 13 GW—based on 70% natural gas and about 30% hydropower—and it has a peak grid-based demand of about 4,500 MW. Only about 3 GW of its installed capacity is operational, however, owing to gas unavailability, water shortages, and infrastructure breakdown. Altogether, about 2.7 GW of generation capacity is lost owing to gas constraints in a country with one of the largest natural gas deposits in the world, up to 0.5 GW is lost to poor water management (Ley et al., 2015). Nigeria is not on track to meet many of its generation capacity expansion targets published in 2006 (Gujba et al., 2010). Because of these challenges, Nigeria decided to privatize the electricity sector in 2013. The benefits of this move will take time to become apparent as the sector restructures. Nigeria is well positioned to integrate large amounts of renewables thanks to its abundance of hydropower and natural gas resources, which can provide the necessary operational flexibility.

METHODOLOGY

The optimization model requires a set of common input variables: a portfolio of existing and potential resources; projections for variable (fuel) and capital costs; annual load forecasts; and characterization of the operational features of the different energy technologies such as resource potential, average capacity factor, and peak contribution. The portfolio of future resources considered are hydropower, geothermal, natural gas and coal, wind, solar photovoltaic, and diesel. The model considers all existing plants in the Kenyan and Nigerian power systems as of 2015. It outputs the annual investment required for the least-cost generation portfolio constrained to meet annual load and peak demand.

The model accounts for non-dispatchable renewables and net load variability by using a peak contribution factor. For example, solar capacity additions in the model contribute 0% capacity to peak demand because Kenya and Nigeria have an evening peak demand, when solar is not available (**Figure *9***). The model also includes a 15% capacity reserve margin to account for reliability. It does not have high geospatial and temporal (hourly) resolution, a trade-off that permits reasonable estimates without large data requirements that would be prohibitive given the state of data availability in some regions of sub-Saharan Africa. This approach also allows for clear sensitivity analysis by duplicating the model over varying scenarios and illustrating the trade-offs in terms of costs, fuel choices, and policy targets. The model's generation capacity estimates are conservative because it includes the peak contribution factor that accounts for the availability of renewables, and its cost estimates are also conservative because it excludes the cost of upgrading existing infrastructure. Therefore, the results should be interpreted as the least estimate of expansion capacity and cost required to alleviate the electricity poverty in the region.

Generation plants are lumped into resource categories: solar PV, wind, biomass, small hydro, large hydro, coal, geothermal, natural gas, and diesel. Natural gas is split into combined cycle and combustion turbine to include variations in how the plants run as baseload or peak capacity. The cost of each resource is split into annualized capital cost ($/kW-yr) and variable cost ($/kWh).

The most recent World Bank commodity price forecasts are used for coal, oil (for diesel and fuel oil), and liquefied natural gas (LNG) (Baffes, 2016). On average, the coal price is $50 a ton, oil is $50 a barrel, and natural gas is $9–12 per MMBtu. Solar PV cost forecasts are taken from a 2015 study developed by the German Fraunhofer Institute (Mayer et al., 2015). Wind, combined cycle, gas turbine, combustion turbine, and coal unit costs come from a 2013 report by the U.S. Energy Information Administration (EIA, 2013). For wind, we assume a linear trend in capital cost reduction of 2% a year, in line with empirical results (Wiser & Bolinger, 2016). Geothermal unit costs are taken from Kenya's least-cost power development plans.

SCENARIOS

The initial least-cost scenario does not have any additional constraints and is referred to the business-as-usual (BAU) scenario. Other environmental and other policy scenarios are explored using additional model constraints. Scenarios are chosen based on pertinent realities in each county. Kenya has plans to build about 4,500 MW of coal to keep up with its demand growth. Nigeria's generation mix is currently dominated by natural gas and hydropower. Both countries are adopting energy efficiency measures as outlined in their power plans. The impact of a carbon tax is explored as well, in line with current global discussions on accounting for the environmental externalities of fossil fuel use.

The optimal generation expansion pathways through 2035 for Kenya and Nigeria are based on the following scenarios:

Kenya

1. **BAU**: This scenario finds the least-cost expansion pathway using a 10% annual demand growth rate.
2. **Low load**: This scenario is based on reduced load and peak demand forecasts, assuming energy efficiency strategies.
3. **Coal**: This scenario constrains the model to install 1,920 MW of coal by 2020 and 4,500 MW of coal by 2030, according to Kenya's medium-term plans.
4. **Carbon tax**: This scenario adds a $40/ton CO2 tax starting in 2016, based on the social cost of carbon.
5. **Carbon tax + 2030 coal**: This scenario constrains the model by adding a $40/ton CO2 tax starting in 2016 and installing 4,500 MW of coal in 2030.

Nigeria

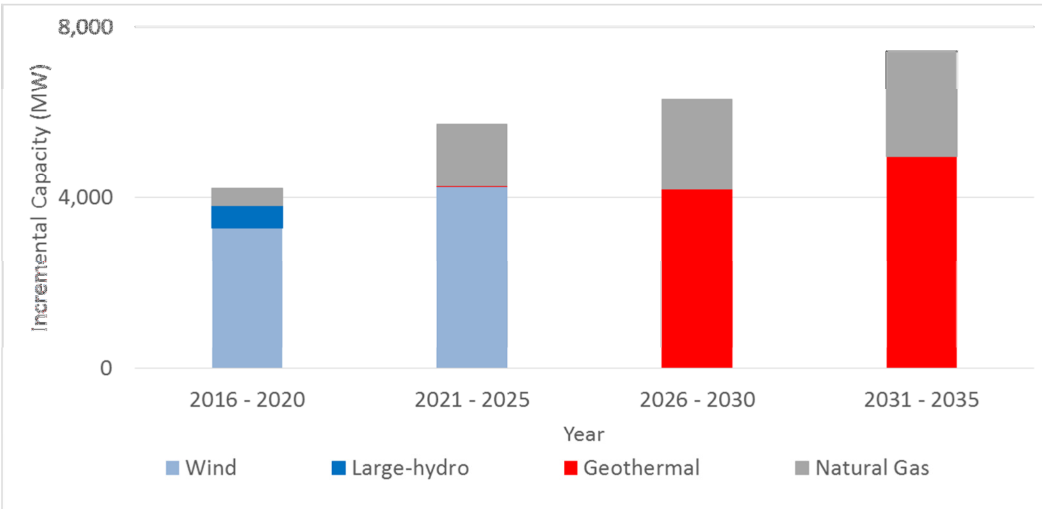
1. **BAU**: This scenario finds the least-cost expansion pathway using a 6% annual demand growth rate.
2. **Low load**: This scenario is based on reduced load and peak demand forecasts, assuming energy efficiency measures.
3. **Gas and hydropower**: This scenario restricts resource potential to natural gas and hydropower only to reflect Nigeria's current fuel choices.
4. **Carbon tax**: This scenario constrains the model by adding a $40/ton CO2 tax starting in 2016, based on the social cost of carbon.

Figures 23–26 display the results in terms of the incremental generation capacity needed in five-year increments—that is, how much additional capacity will be needed in each five-year period to meet the conditions of each scenario by 2035. Tables 2–5 show the total cost and levelized cost of each scenario's generation portfolio.

Business-as-usual scenario

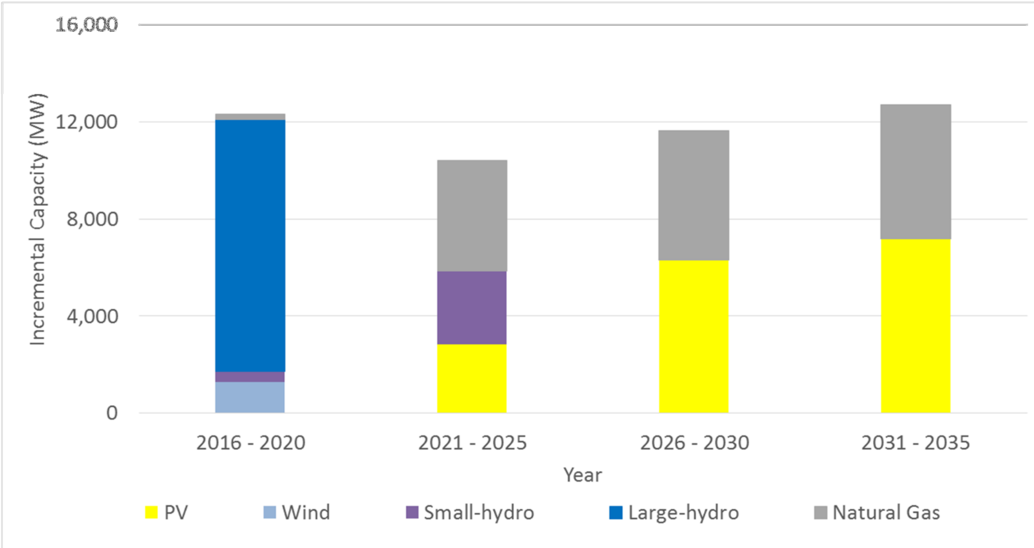
The model results show that Kenya's load growth can be met sustainably and cost-effectively predominantly with geothermal and wind resources, together with some natural gas (Figure 23). Coal is not an economically optimal choice. Most of Kenya's generation capacity additions occur later in the time horizon, between 2030 and 2035.

Figure 23: Incremental capacity expansion under the BAU scenario in Kenya



Nigeria will need more generation capacity than its current plans to meet its existing demand and forecasted demand growth. Nigeria has so much unmet demand today compared with its existing capacity that more than 10 GW of additional capacity is required every five years. The least-cost expansion pathway for Nigeria includes hydropower, natural gas, and solar PV (Figure 24). Coal is not economically optimal in this case either. Generation expansion plans must be coupled with extensive transmission and distribution system upgrades (those costs are not included here).

Figure 24: Incremental capacity expansion under the BAU scenario in Nigeria

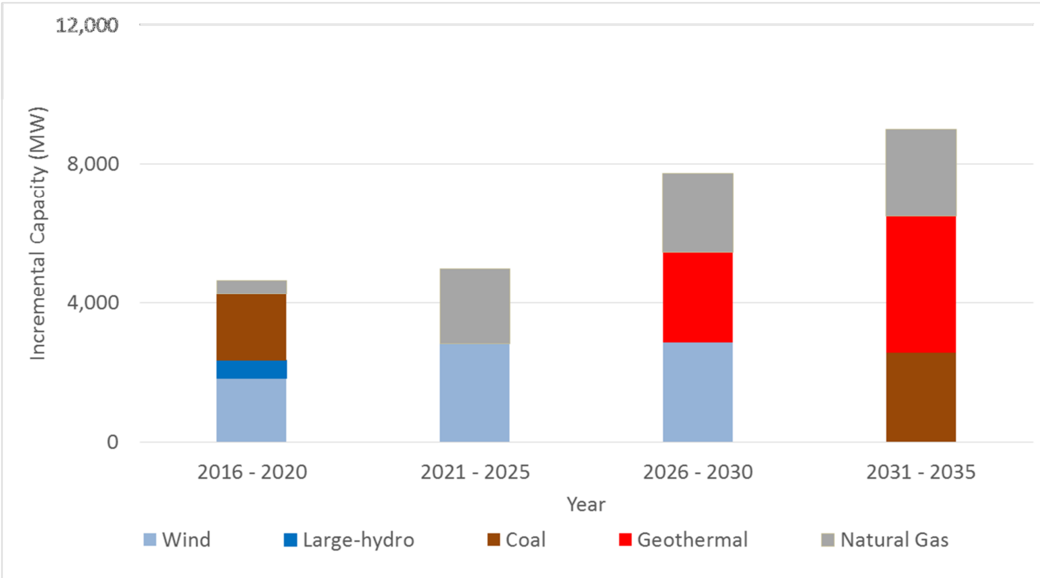


Coal scenario in Kenya

Generation technology choices will be locked in for at least 30 years because generation assets are long-lived and time is required to recover investments in them. Therefore, it is important to demonstrate the significant economic and environmental and social trade-offs involved in transitioning to a low-carbon grid. To determine the trade-offs of coal development in Kenya, the model was constrained to include Kenya's plans of 4,500 MW of coal in 2030. Coal is not identified as the least-cost electricity source in any of the scenarios examined for Kenya and Nigeria. Under our assumptions, the model shows that Kenya's plan to add 4,500 MW of coal by 2030 increases generation costs by about $2 billion in 2035 compared with the BAU pathway. The model shows that coal displaces geothermal generation, which is a clean and cheap baseload generation source (Figure 25).

Coal development will result in significant environmental and public health risks for local communities in Kenya's Kitui and Lamu Counties, where the local coal is found, and also in coastal areas for imported coal. It locks Kenya into a technology many countries are eschewing. Operationally, coal provides baseload capacity and cannot rapidly respond to system variations as natural gas does. If it chooses to develop coal plants, Kenya may still need to add flexibility to its system in the form of gas turbines, diesel engines, or energy storage.

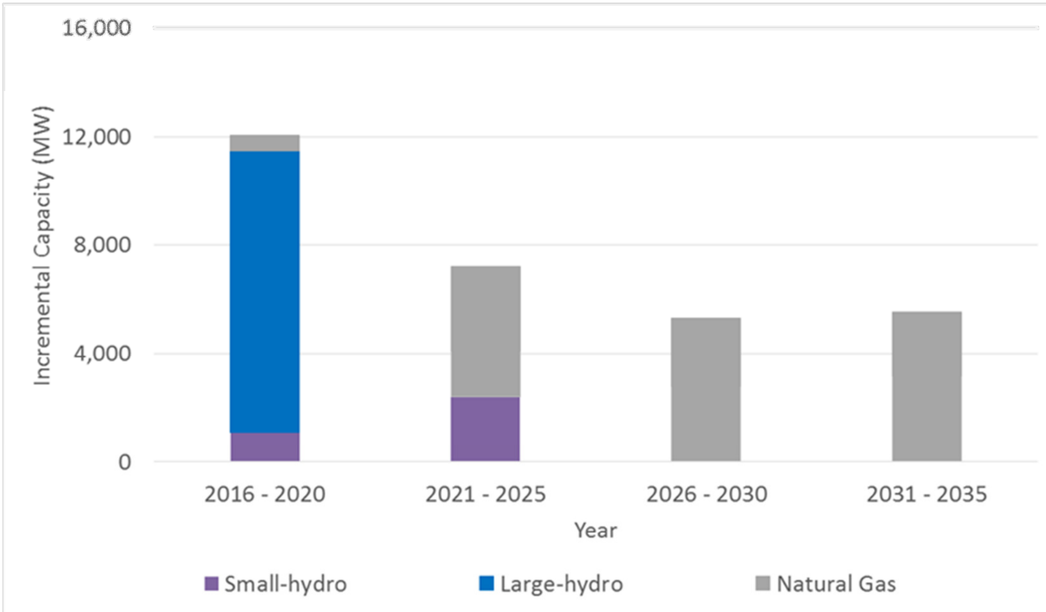
Figure 25: Incremental capacity expansion under the coal scenario in Kenya



Gas and hydropower scenario in Nigeria

If Nigeria restricts generation options to hydropower and natural gas, as it currently has, its generation costs over 2016–2035 will be $6.5 billion more than a diversified BAU pathway that includes solar PV. Developing Nigeria's renewable resources and reducing its dependence on natural gas and hydropower is the economically sound expansion pathway and has the added benefit of preserving the environment. The magnitude of incremental capacity required from 2025 to 2035 appears less when only natural gas is chosen because gas has a higher capacity value than solar, so fewer megawatts of gas are needed to meet the same amount of load (Figure 26). This does not mean, however, that it is a cheaper expansion pathway (Table 2).

Figure 26: Incremental capacity expansion under the natural gas and hydropower scenario in Nigeria



Low load scenario

In the low-load scenario, energy efficiency strategies for achieving lower-than-expected demand growth in Kenya would lead to reductions in total cumulative capacity of about 5 GW and savings of about $5 billion (about 25%) in total generation costs compared with the BAU scenario (Table 1). Similarly, a low-load scenario featuring energy-efficient growth in Nigeria could save 7 GW of new capacity installment and $10 billion (about 11%) in system generation costs (

Table ***2***). In these scenarios, the same types of generation resources are chosen, but less of each resource is deployed, resulting in lower costs.

Carbon tax scenario

Because of the availability and affordability of geothermal and wind resources in Kenya, and solar and hydropower in Nigeria, the BAU scenarios result in clean-energy portfolios without the need to internalize emissions damage through cost instruments such as carbon taxes. By 2035 the share of annual generation coming from renewable sources, excluding large hydropower, would be 90% in Kenya (due to its abundant geothermal resources) and about 30% in Nigeria.

As a result, the carbon tax scenario, which applies a carbon tax of $40/ton of CO2, has no significant impact on the types of resources used to fill the electricity gap. In Kenya the carbon tax increases costs by $0.5 billion, about 2% of the least-cost pathway, because the BAU mix there is already dominated by low-carbon technologies. In Nigeria it increases costs by about $10 billion, about 10% of the least-cost pathway, because Nigeria relies more heavily on natural gas.

If Kenya proceeds with future coal plans, however, a carbon tax will have significant impacts. Including a carbon tax in the 4,500 MW plan for coal increases cost by more than $6 billion compared with the BAU scenario.

SUMMARY OF RESULTS

Table 1: Cost of expanding electricity generation capacity under various scenarios in Kenya

Scenario	NPV (billions of $)	Difference in NPV compared with BAU scenario (billions of $)	LCOE ($/MWh)
BAU	21		46
Low load	16	(5)	46
Coal	24	3	51
Carbon tax	22	0.5	47
Carbon tax + coal	28	7	59

Table 2: Cost of expanding electricity generation capacity under various scenarios in Nigeria

Scenario	NPV (billions of $)	Difference in NPV compared with BAU scenario (billions of $)	LCOE ($/MWh)
BAU	86		72
Low load	77	(10)	71
Natural gas and hydropower	92	6	77
Carbon tax	96	10	80

Table 3: Cumulative installed generation capacity by 2035 under various scenarios in Kenya

Source	2035 capacity (GW) by scenario			
	BAU	**Low load**	**Coal**	**Carbon tax**
PV	0	0	0	0
Wind	8	8	8	8
Biomass	0	0	0	0
Small hydro	0	0	0	0
Large hydro	1	1	1	1
Coal	0	0	5	0
Combined cycle natural gas	0	0	0	0
Diesel	1	1	1	1
Geothermal	10	5	7	10
Simple cycle natural gas	6	4	7	6
Total	**26**	**19**	**28**	**26**

Note: Kenya must add at least 19 GW of capacity to meet demand by 2035.

Table 4: Cumulative installed generation capacity by 2035 under various scenarios in Nigeria

Source	2035 capacity (GW) by scenario			
	BAU	**Low load**	**Natural gas and hydropower**	**Carbon tax**
PV	16	12	0	16
Wind	1	1	0	1
Biomass	0	0	0	0
Small hydro	3	4	3	3
Large hydro	11	11	11	11
Coal	0	0	0	0
Combined cycle natural gas	4	4	11	4
Diesel	0	0	0	0
Geothermal	0	0	0	0
Simple cycle natural gas	17	13	10	17
Total	**53**	**45**	**36**	**53**

Note: Nigeria must add at least 36 GW of capacity to meet demand by 2035.

PATHWAY TRADE-OFFS

Given the abundance of renewable resources on the continent, countries have significant potential to use variable renewable energy to provide baseload capacity by integrating geographically diversified sources and employing existing grid flexibility as described. This ability depends partly on the existing fuel mix of the grid, but because power systems in sub-Saharan Africa are relatively young, expansion could be carried out strategically to accommodate large penetrations of variable renewable resources. For example, countries with large hydropower and natural gas capacities in existing grids can cost-effectively transition to large-scale integration of renewable resources (as seen in the Kenya and Nigeria case studies), and even more so by enabling regional energy trading.

Fossil fuels will play a role in the region's transition because of its existing installed capacity and the ability of resources such as natural gas and diesel to provide system flexibility. As energy storage costs decline, the need for gas and diesel may be displaced. Although renewable generation now has costs similar to that of fossil fuels and avoids the associated environmental risks, a 100% renewable grid will require large-scale storage owing to load fluctuations, unexpected weather changes, unexpected plant and grid outages, and solar and wind variability.

The economic, environmental, and political trade-offs and impacts of sub-Saharan Africa's fuel choices, as seen through the case studies are the following:

1. Coal development will subject communities to significant environmental degradation and public health risks. This risk exposure is unnecessary because cheap renewable alternatives are available, as shown in Kenya and Nigeria. In countries without cheaper and cleaner alternatives to coal, regional cooperation through power pools offers a viable way of meeting electricity demand sustainably. The Kenya and Nigeria case studies show that governments should consider coal development plans carefully and cautiously. They also underline the need for accessible data on the power systems of other countries in the region, because the potential environmental costs of choosing coal today are large.

2. Building coal power plants today as a stopgap on the way to transitioning to renewable energy may cause path dependency and lock countries into a suboptimal expansion pathway that is economically and environmentally expensive.

3. Power systems built for coal are different from power systems built for renewables, and deploying coal today may thus determine system characteristics, such as operational flexibility, that may limit future integration of renewables.

4. There are economic trade-offs between low-capital-cost/high-variable-cost resources (typically coal, natural gas, and diesel) and high-capital-cost/low-variable-cost resources (typically renewables such as solar and wind). These trade-offs are important to consider for capital-scarce sub-Saharan countries and may also have implications for countries' trade balance and exposure to financial risks.

SUMMARY

This chapter demonstrates the economic, environmental, and operational trade-offs involved in filling the electricity gap in sub-Saharan Africa, but these trade-offs are context specific and require power system modeling, which is prohibitive for many countries in the region owing to the lack of data. The case studies of Kenya and Nigeria show that renewables are cost competitive and that fuels such as natural gas can play a role in providing system flexibility until grid storage costs decline. The case studies also show that the scale of centralized generation expansion required to meet moderate load growth by 2035 is significant compared with many countries' historical investments in power systems and rate of system expansion. The region has underinvested for a number of years: current investment in sub-Saharan electricity systems is about US$8 billion a year. This is inadequate to overcome the existing shortfall in infrastructure, to expand access and coverage, and to meet growth in demand (Cartwright, 2015). Grid-based power generation capacity in all of sub-Saharan Africa increased by 22 GW from 2000 to 2012, from about 68 GW to 90 GW, with South Africa alone accounting for about half of the total (IEA, 2014). The model shows that Nigeria alone will have to install at least an additional 36 GW by 2035 to keep up with grid-based load growth alone.

To achieve full electricity access, sub-Saharan Africa must rely on a combination of many pathways and strategies, such as synergies between centralized and distributed energy systems, bolstered financial support and investment, and improved institutional capacity and management. Providing affordable and reliable electricity for all in sub-Saharan Africa will require unprecedented financial, social, and political efforts.

9. CONCLUSION

This report has provided an account of the state of the power sector in sub-Saharan Africa, and the challenges and opportunities of various power expansion pathways. We have shown that the renewable energy potential in the region is abundant, and the costs are declining and reaching parity with conventional generation resources. We have also shown that the investment and planned use of fossil fuels should be judicious given that decades of its development in the region have done little to increase energy access. It is critical that fuel choices be considered cautiously, particularly coal, which proved to be a costly pathway to electrification in Kenya and Nigeria. The successful transition to high penetrations of renewables will depend on various sources of system flexibility, particularly natural gas and grid storage, and on the effective operation of regional power pools. Also, we emphasize that distributed and centralized energy systems will have to be strategically deployed to operate in synergy and complement each other over their operational lifetimes.

Lack of data access and availability in sub-Saharan Africa hinders robust power system analysis from informing many countries' policy decisions. This situation risks locking the region into a development path that is economically and environmentally suboptimal for its people. Attaining 100% electricity access rapidly across the region will require a mix of pathways and scales.

The narrative around the electricity gap in sub-Saharan Africa has been dominated by disconnected questions. Where should supply come from—fossil fuels or renewables? What scale of infrastructure should be deployed to reach unconnected populations—centralized grid extensions or distributed systems? In contrast, we redefine the electricity gap as an integral problem that involves supply-demand mismatches, inequality, and electricity access decisions—it is ultimately a social and technical challenge. In our view, the conventional approach relying on fossil fuels and grid extensions is being superseded by a new paradigm based on renewable resources and scale-appropriate technologies. These elements will be at the core of public and private decisions to empower sub-Saharan Africa in the coming decades.

Table A1: Country classification

Sub-Saharan Africa			
Eastern Africa	*Western Africa*	*Middle Africa*	*Southern Africa*
Burundi	Benin	Angola	Botswana
Comoros	Burkina Faso	Cameroon	Lesotho
Djibouti	Cape Verde	Central African Republic	Namibia
Eritrea	Côte d'Ivoire	Chad	South Africa
Ethiopia	Gambia	Congo	Swaziland
Kenya	Ghana	Democratic Republic of the Congo	
Madagascar	Guinea	Equatorial Guinea	
Malawi	Guinea-Bissau	Gabon	
Mauritius	Liberia	Sao Tome and Principe	
Mozambique	Mali		
Rwanda	Mauritania		
Seychelles	Niger		
Somalia	Nigeria		
Sudan	Senegal		
Uganda	Sierra Leone		
United Republic of Tanzania	Togo		
Zambia			
Zimbabwe			

REFERENCES

Ackermann, T., Brown, T., Langanke, S., and Narasimhan, B. (2014). Analysis of the stability of the Kenyan power system. Energynautics GmbH, Germany.

Africa Progress Panel. (2015). *Power, people, planet: Seizing Africa's energy and climate opportunities: Africa progress report 2015*. Geneva.

African Development Bank. (2013). The high cost of electricity generation in Africa. Championing Inclusive Growth Across Africa blog, February 18.

Afrobarometer. (2016). AD75: Off-grid or 'off-on': Lack of access, unreliable electricity supply still plague majority of Africans. http://afrobarometer.org/publications/ad75-unreliable-electricity-supply-still-plague-majority-of-africans.

Ansar, A., Flyvbjerg, B., Budzier, A., and Lunn, D. (2014). Should we build more large dams? The actual costs of hydropower megaproject development. *Energy Policy* 69: 43–56.

Baffes, J. (2016). *Commodity market outlook*. Washington, DC: World Bank.

Bazilian, M., Nussbaumer, P., Rogner, H.-H., Brew-Hammond, A., Foster, V., Pachauri, S., Williams, E., et al. (2012). Energy access scenarios to 2030 for the power sector in sub-Saharan Africa. *Utilities Policy* 20: 1–16. doi:10.1016/j.jup.2011.11.002.

Bhatia, M., & Angelou, N. (2015). *Beyond connections: Energy access redefined*. Washington, DC: World Bank.

Cartwright, A. (2015). *Better growth, better cities: Rethinking and redirecting urbanisation in Africa*. Working Paper. London and Washington, DC: New Climate Economy.

Carvallo, J. P., Avila, N., Shaw, B., & Kammen, D. M. (Under review) Sustainable growth for the power sector of an emerging economy: The case of Kenya.

Casillas, C., & Kammen, D. M. (2010). The energy-poverty-climate nexus. *Science*, 330, 1181–1182.

Castellano, A., Kendall, A., Nikomarov, M., & Swemmer, T. (2015). *Brighter Africa: The growth potential of the sub-Saharan electricity sector*. McKinsey Report. http://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/powering-africa

Chu, S., & Majumdar, A. (2012). Opportunities and challenges for a sustainable energy future. *Nature* 488,7411: 294–303.

Clifford, M. L. (2016). Watch out, coal! Dubai announces plans for world's lowest cost solar plant. *Forbes*, June 29. www.forbes.com/sites/mclifford/2016/06/29/cheaper-than-coal-dubai-to-build-worlds-lowest-cost-solar-plant/#728cbb72a346.

Climate Vulnerable Forum. (2016). The CVF Vision. November 18 http://www.thecvf.org/marrakech-vision/.

Cochran, J., et al. (2014). *Flexibility in 21st century power systems*. Technical Report NREL/TP-6A20-61721. Golden, CO: National Renewable Energy Laboratory.

Denholm, P., O'Connell, M., Brinkman, G., & Jorgenson, J. (2015). *Overgeneration from solar energy in California: A field guide to the duck chart*. Technical Report NREL/TP-6A20-65023. Golden, CO: National Renewable Energy Laboratory.

Eberhard, A., Gratwick, K., Morella, E., & Antmann, P. (2016). *Independent power projects in Sub-Saharan Africa: Lessons from five key countries*. Washington, DC: World Bank.

EIA (Energy Information Administration). (2013). *Updated capital cost estimates for utility scale electricity generating plants*. Washington, DC

Foster, V., & J. Steinbuks. (2009). *Paying the price for unreliable power supplies: In-house generation of electricity by firms in Africa*. Policy Research Working Paper. Washington, DC: World Bank.

GeoSUN Africa (2011). Global horizontal irradiation: Africa and Middle East. http://geosun.co.za/wp-content/uploads/2012/07/SolarGIS-Solar-map-Africa-and-Middle-East-en.png.

Global CCS Institute. (n.d.). Understanding carbon capture and storage. http://www.globalccsinstitute.com/understanding-ccs.

Gujba, H., Mulugetta, Y., & Azapagic, A. (2010). Environmental and economic appraisal of power generation capacity expansion plan in Nigeria. *Energy Policy* 38,10: 5636–5652.

IEA (International Energy Agency). (2014). *Africa energy outlook: A focus on energy prospects in sub-Saharan Africa*. Paris.

IEA (International Energy Agency). (2016). *World energy outlook 2016*. Paris.

IRENA (International Renewable Energy Agency). (2015). *Africa clean energy corridor: Analysis of infrastructure for renewable power in Eastern and Southern Africa*. Abu Dhabi. www.irena.org/DocumentDownloads/Publications/IRENA_Africa_CEC_infrastructure_2015.pdf.

IRENA (International Renewable Energy Agency). (2016). *Solar PV in Africa: Cost and markets*. Bonn.

Kalitsi, E. A. K. (2003). *Problems and prospects for hydropower development in Africa.* Report prepared for the Workshop for African Energy Experts on Operationalizing the NEPAD Energy Initiative, June 2–4, Dakar, Senegal.

Kammen, D. M., Jacome, V., & Avila, N. (2015). *A clean energy vision for East Africa*. Berkeley, CA: Renewable and Appropriate Energy Laboratory, University of California, Berkeley.

Kang, Y., Khan, S., & Ma, X. (2009). Climate change impacts on crop yield, crop water productivity, and food security: A review. *Progress in Natural Science* 19.12: 1665–1674.

Kenning, T. (2015). ABB to minimise diesel in Africa micro-grids using flywheels and batteries with renewables. *Energy Storage News*, September 9. http://www.energy-storage.news/news/abb-to-minimise-diesel-in-africa-micro-grids-using-flywheels-and-batteries.

Lazard. (2013). Lazard's levelized cost of energy analysis, version 7.0. New York.

Leslie, J. (2016). One of Africa's biggest dams is falling apart. *The New Yorker*, February 2.

Ley, K., Gaines, J., & Ghatikar, A. (2015). *An overview with a special emphasis on renewable energy, energy efficiency, and rural electrification*. Bonn: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ).

Mayer, J., Phillips, S., Saad Hussein, N., Schlegl, T., & Senkpiel, C. (2015). *Current and future cost of photovoltaics: Long-term scenarios for market development, system prices, and LCOE of utility-scale PV systems*. 059/01-S-2015/EN. Berlin: Fraunhofer-Institute for Solar Energy Systems (ISE).

Mobisol. (2017). Products. www.plugintheworld.com/mobisol/product/.

PowerGen. (2017). Our microgrids are the building blocks of Africa's future smart grid. www.powergen-renewable-energy.com/micro-grids-for-the-future-of-power/.

PwC (PricewaterhouseCoopers). (2016). Electricity beyond the grid: Accelerating access to sustainable power for all. www.pwc.com/gx/en/energy-utilities-mining/pdf/electricity-beyond-grid.pdf.

Román, M. (2011). Carbon capture and storage in developing countries: A comparison of Brazil, South Africa, and India. *Global Environmental Change* 21,2: 391–401.

Sanoh, A., Kocaman, A. S., Kocal, S., Sherpa, S., & Modi, V. (2014). The economics of clean energy resource development and grid interconnection in Africa. *Renewable Energy* 62: 598–609.

Schnitzer, D., Lounsbury, D. S., Carvallo, J. P., Deshmukh, R., Apt, J., & Kammen, D. M. (2014). *Microgrids for rural electrification: A critical review of best practices based on seven case studies*. Washington, DC: United Nations Foundation. http://energyaccess.org/wp-content/uploads/2015/07/MicrogridsReportFINAL_high.pdf.

Siegfried, K. (2014). South Africa's coal-fired power stations carry heavy health costs. Guardian Development Network, September 9.

Sparrow, F. T., Masters, W., Bowen, B. H., & Metzel, J. C. (2002). *Electricity trade and capacity expansion options in West Africa*. West Lafayette, IN: Purdue University.

Szabo, S., Bodis, K., Huld, T., & Moner-Girona, M. (2011). Energy solutions in rural Africa: Mapping electrification costs of distributed solar and diesel generation versus grid extension. *Environmental Research Letters* 6,3: 034002.

Ueckerdt, F., & Kempener, R. (2015). *From baseload to peak: Renewables provide a reliable solution*. Working Paper. Abu Dhabi: International Renewable Energy Agency (IRENA). www.irena.org/DocumentDownloads/Publications/IRENA_Baseload_to_Peak_2015.pdf.

Union of Concerned Scientists. (2016). Environmental impacts of hydroelectric power. http://www.ucsusa.org/clean_energy/our-energy-choices/renewable-energy/environmental-impacts-hydroelectric-power.html#.WIde8JKRX-B.

Vergragt, P. J., Markusson, N., & Karlsson, H. (2011). Carbon capture and storage, bio-energy with carbon capture and storage, and the escape from the fossil-fuel lock-in. *Global Environmental Change* 21,2: 282–292.

Whitley, S., & van der Burg, L. (2015). *Fossil fuel subsidy reform in sub-Saharan Africa: From rhetoric to reality*. Working Paper. London and Washington, DC: New Climate Economy.

Wiser, R. H., & Bolinger, M. (2016). *2015 wind technologies market report*. Berkeley, CA: Lawrence Berkeley National Laboratory.

World Bank. (2014). Electric power consumption (kWh per capita). http://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC.

Wu, G. C., Deshmukh, R., Ndhlukulac, K., Radojicic, T., Reilly, J. (2015) Renewable Energy Zones for the Africa Clean Energy Corridor. International Renewable Energy Agency and Lawrence Berkeley National Laboratory, LBNL (LBNL-187271).

RESEARCH BACKGROUNDER SERIES LISTING

"Making Investments in Poor Farmers Pay: A Review of Evidence and Sample of Options for Marginal Areas," by Melinda Smale and Emily Alpert (2009).

"Turning the Tables: Global Trends in Public Agricultural Investments," by Melinda Smale, Kelly Hauser, and Nienke Beintema, with Emily Alpert (2009).

"Risk and Risk Transfer in Agriculture: Facilitating Food Security and Poor Farmer Participation," by Leander Schneider (2010).

"From the Ground Up: Strategies for Global Community-based Disaster Risk Reduction," by Kelly Hauser (2010).

"Impact of Climate Change on Response Providers and Socially Vulnerable Communities in the US," by John Cooper and Jasmine Waddell (2010).

"Climate Change and Violent Conflict: A Critical Literature Review," by Ellen Messer (2010).

"Under Pressure: Reducing Disaster Risk and Enhancing US Emergency Response Capacity in an Era of Climate Change," by Marc Cohen, Kelly Hauser, Ellen Messer, and M. Cristina Tirado (2011).

"Impact of Garment and Textile Trade Preferences on Livelihoods in Cambodia," by Sophal Chan and Sothea Oum (2011).

"In Need of a Better WASH: Water, Sanitation, and Hygiene Policy Issues in Post-earthquake Haiti," by Figaro Joseph (2011).

"Local Capacity in Humanitarian Response: Vision or Mirage?," by Michael Delaney and Jacobo Ocharan (2012).

"Systems, Power and Agency in Market-based Approaches to Poverty," by Chris Jochnick (2012).

"Measuring Economic Progress and Well-Being: How to move beyond GDP?," by Heloisa Marone (2012).

"Land Rights, Land Tenure, and Urban Recovery: Rebuilding Post-Earthquake Port-au-Prince and Léogâne," by Harley F. Etienne (2012).

"Haiti Rice Value Chain Assessment: Rapid Diagnosis and Implications for Program Design," by David C. Wilcock and Franco Jean-Pierre (2012).

"From Controversy to Consensus: Lessons Learned from Government and Company Consultations with Indigenous Organizations in Peru and Bolivia," edited by Emily Greenspan (2012).

"Community Consent Index: Oil, Gas, and Mining Company Public Positions on Free, Prior, and Informed Consent (FPIC)," by Marianne Voss and Emily Greenspan (2012).

"Harvesting Data: What Can 10 Years of Official Development Assistance Data Tell Us About US International Agricultural Development?," by Kelly Hauser (2012).

"US Investment in Large-scale Land Acquisitions in Low- and Middle-Income Countries," by Joshua Humphreys, Ann Solomon, and Emmanuel Tumusiime (2013).

"Local Institutions, External Interventions, and Adaptations to Climate Variability: The case of the Borana pastoralists in southern Ethiopia," by Dejene Negassa Debsu (2013).

"Local Institutions, External Interventions, and Adaptations to Climate Variability: The case of southern Mali," by Rebecca JoyHoward (2013).

"The Power of Oil Palm: land grabbing and impacts associated with the expansion of oil palm crops in Guatemala: The case of the Palmas del Ixcan Company," by Arantxa Guerena and Ricardo Zepeda (2013).

"Human Rights and Social Conflict in Oil, Gas, and Mining Industries: Policy recommendations for national human rights institutions," by Ben Collins and Lesley Fleischman (2013).

"The Rice Value Chain in Haiti: Policy proposal," by Carlos Furche (2013).

"Housing Delivery and Housing Finance in Haiti: Operationalizing the national housing policy," by Duong Huynh, et al. (2013).

"Development Assistance on Local Adaptive Capacity to Climate Change: Insights from Senegal," by Henri M. Lo and Emmanuel Tumusiime (2013).

"Agriculture Change, Land, and Violence in Protracted Political Crisis: An examination of Darfur," by Abdal Monium K. Osman, Helen Young, Robert F. Houser, and Jennifer C. Coates (2013).

"Sustainable and inclusive Investments in Agriculture: Lessons on the Feed the Future Initiative in Tanzania," by Emmanuel Tumisiime and Demund Matotay (2014).

"Feed the Future Investment in Haiti: Implications for sustainable food security and poverty reduction," by Danielle Fuller Wimbush and Cardyn Fil-Aime (2014).

"Delivering Aid in contested Spaces: Afghanistan," by Erin Blankenship (2014).

"The Drivers of Economic Inequality: A Primer," by Nick Galasso (2014).

"Ready for old? Assessing Haiti's governance and regulatory capacity for large-scale mining," by Scott Sellwood and Stuart Levit (2015).

"Global Reach of the US Financial Sector," by Stephanie Fontana (2015).

"Climate change, equity and stranded assets," by Simon Caney (2016).

"Gender and Social Accountability: Ensuring women's inclusion in citizen-led accountability programming relating to extractive industries," by Sarah Bradshaw with Brian Linneker and Lisa Overton (2016).

"Transformative and Feminist Leadership for Women's Rights," by Shawna Wakefield (2017)

"The energy challenge in sub-Saharan Africa: A guide for advocates and policy makers: Part 1: Generating energy for sustainable and equitable development," by Nkiruka Avila, Juan Pablo Carvallo, Brittany Shaw and Daniel Kammen (2017).

"The energy challenge in sub-Saharan Africa: A guide for advocates and policy makers: Part 2: Addressing energy poverty," by James Morrissey (2017).

Oxfam is a global movement of people working together to end the injustice of poverty. With 70 years of experience in more than 90 countries, Oxfam takes on the big issues that keep people poor: inequality, discrimination, and unequal access to resources including food, water, and land. We help people save lives in disasters, build stronger futures for themselves, and hold the powerful accountable. Join us. **www.oxfamamerica.org.**

OXFAM

US HEADQUARTERS
226 CAUSEWAY STREET, 5TH FLOOR
BOSTON, MA 02114-2206
(800) 77-OXFAM

US POLICY & ADVOCACY OFFICE
1101 17TH STREET, NW, SUITE 1300
WASHINGTON, DC 20036
(202) 496-1180

www.oxfamamerica.org