Atoms for Africa: Is There a Future for Civil Nuclear Energy in Sub-Saharan Africa?

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Abstract

This paper explores the feasibility of commercial nuclear power in sub-Saharan Africa, especially in light of advanced nuclear technologies and their potential to overcome some of the challenges to deployment. The authors find significant interest in and steady progress toward commercial nuclear power in several sub-Saharan African countries, yet most countries are at least a decade away from breaking ground on their first project. Development organizations that finance energy issues should stay informed about the progress African countries are making on nuclear and should consider the technology in their ongoing discussions around options for increased energy access and generation.

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Preface

CGD's work on energy has focused largely on definitions of energy access, data analysis, and the efficacy of international tools to spur investment in the power sector in developing countries. Yet as many African countries continue to experience vastly under-developed power sectors, policymakers have begun considering the potential of next generation nuclear power to meet some of the continent's future energy demand. Several countries are actively exploring nuclear power deals, yet the major international infrastructure financiers—like the World Bank—have no expertise or mandate to advise on nuclear energy. To better understand the status, opportunities, and risks of nuclear power in Africa, we commissioned this paper from Abigail Sah, Jessica Lovering, Omaro Maseli, and Aishwarya Saxena of the Breakthrough Institute, a think tank based in Oakland, CA. The authors outline the web of challenges that African countries face in pursuing advanced nuclear technologies to meet their energy needs.

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Introduction

In the face of increasing concern about human-caused climate change, there is an urgent need for a global transition to clean energy. Yet in many parts of the world, such as sub-Saharan Africa, there is also a need for significant increases in energy consumption to improve human development. The focus of this report is one—often overlooked—pathway to meet these twin challenges of alleviating energy poverty and minimizing greenhouse gas emissions: nuclear energy.

Despite being home to a diverse range of energy resources—from oil and gas in the west to strong hydro-potential in more central regions—Africa still lays claim to severely under-developed power sectors in most of its sub-Saharan countries.[1] Instead, the region faces a power infrastructural deficit requiring upwards of $90 billion annually to resolve.[2] Taken together, the 48 countries that make up sub-Saharan Africa generate approximately the same amount of power as Spain, despite having a population that is 18 times larger.[3] As of 2012, the sub-Saharan 48 had a mere 83 gigawatts (GW) of total grid-connected generation capacity, with South Africa alone accounting for more than half of that.[4]

The 2014 *Africa Energy Outlook* indicates that some 625 million people in Africa do not have access to electricity, while another estimated 730 million Africans on the continent use dirty and potentially hazardous fuels to cook.[5] Furthermore, average per capita residential electricity consumption was placed at 317kWh per year.[5] Yet despite these meager numbers, between 1990 and 2013 only $45.6 billion was invested in the power sector—that is, half of what is required annually. Sub-Saharan Africa has therefore found itself in a situation where its rapidly growing population, expected to reach 2.8 billion by 2060, urgently requires innovative energy solutions capable of guaranteeing a sustained growth in energy supply.[6]

Historically, many emerging economies have turned to nuclear power to meet energy deficits, and there is immense potential for nuclear to provide a clean baseload source of energy to meet Africa's large energy deficit while also minimizing carbon emissions. Fossil fuel power plants like oil, coal, and gas not only pollute but must have a constant delivery of fuel, which can be a challenge where transportation and pipeline infrastructure is underdeveloped.[1] Kenny (2008) argues that since nuclear power plants (NPPs) have fewer siting constraints due to the small size and extremely dense fuel, they could be located closer to load centers to avoid the transmission costs, which could be high in African countries where there are larger distances between significant population centers.[1] Additionally, nuclear technology could be used for other non-power uses on the continent such as desalination and industrial process heat.

Unsurprisingly, there appears to be substantial interest in nuclear power across Africa. In 2015, representatives from Egypt, Ghana, Kenya, Morocco, Niger, Nigeria, South Africa, Sudan, Tunisia and Uganda began preliminary plans to set up the African Network for Enhancing Nuclear Power Programme Development, aimed at strengthening and building capacity across the African continent for the planning, development, and management of nuclear power infrastructure and programs.[7] The first African Nuclear Youth Summit was held in Kenya in March 2017, with attendees from Ghana, Kenya, Namibia, Nigeria, and

Sudan, along with all North African countries.[8] Over time, the international nuclear safety framework has also evolved into one that is more globalized and fosters more international collaboration. The IAEA has sent review teams to South Africa in 2013, to Kenya, Nigeria, and Morocco in 2015, and to Ghana in 2017.[8]

Despite the potential of and interest in nuclear power in sub-Saharan Africa, there remain significant challenges to adopting the technology on the continent. For one, current NPPs on the market, at a power rating of 1,000 megawatts (MW) or more, exceed the capacity that many African countries can support. (There is a rule of thumb that no power plant in a country should have a capacity that exceeds 10 percent of that country's total grid capacity.[9]) High capital costs, low human capital, weak institutional quality, long times required to develop robust legal and regulatory frameworks, and proliferation concerns of nuclear fuel also serve as barriers to the adoption of nuclear technology on the continent.[1] For these reasons, only South Africa has an operating nuclear power plant, with 1,800 MW of capacity made up of two units of pressurized water reactors.[10] South Africa plans to expand their nuclear capacity by 9,600 MW, and aims to increase the share of the country's electricity from nuclear from 5 percent to 25 percent by 2025.

Jewell (2011) conducted an assessment on the feasibility of developing 1,000MW or larger nuclear power plant in 52 emerging nuclear countries, including 14 African countries.[11] Jewell's assessment characterized the motivation and capacity of each country to develop nuclear power by using such metrics as electricity grid size, GDP per capita, and the World Bank Government Effectiveness Indicator amongst others to categorize where each country stood in the quest to develop nuclear power.[11] Of the 14 African countries accessed, only 2 were classified as nuclear power development being possible, but only with international support. Of the other 12 countries, the likelihood of the development of nuclear power was classified as being uncertain in 3 of the countries and unlikely in 9.[11]

The challenges are considerable, but there is reason for optimism. Small Modular Reactors (SMRs) and advanced nuclear technologies could improve the feasibility of developing commercial nuclear power in African countries. Through smaller reactor sizes, passive safety, and simplified design, these new nuclear technologies could be easier to finance, construct, and operate.

This paper explores the feasibility of commercial nuclear power in sub-Saharan Africa, especially in light of advanced nuclear technologies and their potential to overcome some of the challenges to deployment. Part 1 outlines the current state of nuclear power deployment in sub-Saharan Africa. Part 2 gives an overview of what the challenges of deploying nuclear power are likely to be. Finally, Part 3 describes advanced nuclear technology and how it could increase the likelihood of nuclear development.

We find that there is significant interest in and steady progress toward commercial nuclear power in sub-Saharan African countries. Yet most countries are still a decade away at least from breaking ground on their first project. Advanced nuclear designs have the potential to mitigate some of the challenges of deployment in this region, but they are also about a decade away from first commercial demonstration. Perhaps a confluence of these two events will allow African countries to leapfrog over the large-scale, traditional light-water nuclear technologies to nuclear technology that is smaller, modular, more flexible, and overall more appropriate. Development organizations that focus on energy issues should stay informed about the progress these countries are making on nuclear, and should consider the technology in their ongoing discussions around options for increased energy access.

Part 1: Current Status of Nuclear Power Deployment in Africa

South Africa is currently the only country on the continent with commercial nuclear power. However, Africa has an active nuclear science and technology sector, including several research reactors, and significant government interest in starting commercial nuclear programs. Below we highlight the progress of sub-Saharan African countries across nuclear science and technology, domestic regulatory development, international safety and security treaties, and commercial nuclear power agreements.

Nuclear Science and Technological Development in Africa

Beyond the pair of commercial reactors in South Africa, research reactors are the primary way African countries engage with nuclear technology and research. There are ten research reactors in eight countries across the continent, all of them built by foreign entities. Table 1 below gives a breakdown of where these reactors are located, their official names, what type they are, who built them, and their capacities.

Table 1. Current nuclear research reactors in Africa[12]

Country	Nuclear Facility Name	Type	Built By	Capacity (kW)
Algeria	Es-Salam (temporary shut down)	Heavy Water	China	15,000
Algeria	Nur	Pool	Argentina	1,000
Democratic Republic of Congo	TRICO-II (extended shut down)	Pool, TRIGA Mark II	US	1,000
Egypt	ETRR-1 (extended shut down)	Tank	USSR	2,000
Egypt	ETRR-2	Pool	Argentina	22,000
Ghana	GHARR-1	MNSR, Tank in pool	China	30
Libya	IRT-1 (temporary Shut down)	Pool, IRT	USSR	10,000
Morocco	MA-R1	TRIGA Mark II	US/France	2,000
Nigeria	NIRR-1	MNSR, Pool	China	30
South Africa	SAFARI-1	Tank in pool	US	20,000

While these research reactors are used for a range of environmental, agricultural, and medical research, they are also often seen as the first step toward a commercial nuclear power program.[12] Research reactors help train scientists and students in nuclear science, radiation protection, and waste management. While there are several universities offering nuclear education in South Africa, a number of other sub-Saharan African countries are now offering courses in nuclear science and engineering. Nigeria graduated its first cohort of master's students in nuclear engineering in 2014.[13] Recognizing the need for more training, the Russian nuclear company Rosatom offers dozens of scholarships to African students to complete nuclear engineering degrees in Russia.[14]

Progress in Domestic Regulatory Formation

Before countries even consider building a commercial nuclear power plant, they need to develop the domestic policy and regulations to support the sector; this is often done through an energy or environmental ministry or often a separate atomic energy agency is created. The IAEA has developed a framework to help emerging nuclear countries create their own regulatory institutions to manage all aspects of nuclear power. The IAEA framework, detailed in *Milestones in the Development of a National Infrastructure for Nuclear Power,* outlines three major development phases, where each phase is completed with a milestone:[15]

- *Phase 1: Considerations before a decision to launch a nuclear power program is taken.* Milestone 1: Ready to make a knowledgeable commitment to a nuclear power program.

- *Phase 2: Preparatory work for the contracting and construction of a nuclear power plant after a policy decision has been taken.* Milestone 2: Ready to invite bids/negotiate a contract for the first nuclear power plant

- *Phase 3: Activities to implement the first nuclear power plant.* Milestone 3: Ready to commission and operate the first nuclear power plant.

During each phase, the country's government must consider specific tasks that fall under 19 infrastructure issues, shown in Table 2 below. The order is not strictly followed, but establishing a national position on nuclear power is generally one of the first tasks and procurement comes toward that end.

Table 2. Infrastructural Issues identified by the IAEA

1	National Position	11	Stakeholders Investment
2	Nuclear Safety	12	Site and Supporting Facilities
3	Management	13	Environmental Protection
4	Funding and Financing	14	Emergency Planning
5	Legislative Framework	15	Security and Physical Protection
6	Safeguards	16	Nuclear Fuel Cycle
7	Regulatory Framework	17	Radioactive Waste
8	Radiation Protection	18	Industrial Involvement
9	Electrical Grid	19	Procurement
10	Human Resources Development		

South Africa, the only African country with a commercial nuclear power plant, has of course completed all three development phases. But Ghana has also achieved success in all the 19 infrastructural issues for Phase 1, involving building national consensus to embark upon a nuclear reactor, as well as establishing the requisite legislative and institutional framework and procuring a reactor.[16] Nigeria is also emerging quickly in this process, having already drafted its law to establish its national regulator. In 2015, the IAEA conducted two missions to Nigeria in support of its nuclear program, which showed that the country had adequate emergency preparedness and response framework in alignment with the IAEA's safety standards (although they also concluded that Nigeria needed to improve its policies on spent fuel and radioactive waste management).[17]

Progress in International Nuclear Safety and Security Treaties

While many may be worried about weapons proliferation and the security of nuclear facilities in developing countries, African countries have made great progress on non-proliferation, with all but two countries ratifying or acceding to the Non-Proliferation Treaty. Over half of the countries have also ratified the Additional Protocols, which allow the IAEA to verify that states are complying with their comprehensive safeguards agreements. Almost all countries have signed the African Nuclear Weapon Free Zone Treaty (Pelindaba Treaty) and a majority have ratified, which prohibits all activities related to nuclear weapons development, transport, and use. Figure 1 below shows which countries are party to which agreements.

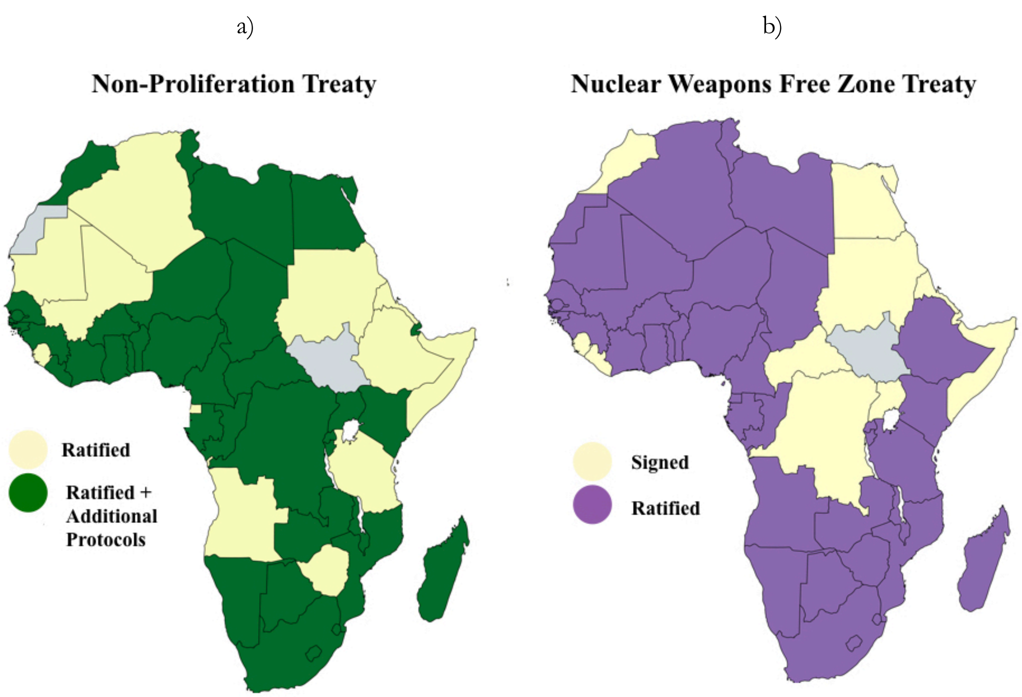


Figure 1. (a) African countries that have ratified the Non-Proliferation Treaty, and those that have also signed the Additional Protocols. (b) countries that have signed the Nuclear Weapons Free Zone Treaty, and those that have signed and ratified the treaty

Beyond these agreements, the US requires that countries have so-called "123 Agreements" before they can import nuclear materials or technology from US companies. Completing a 123 Agreement involves a Nuclear Proliferation Assessment Statement completed by the US Department of State, which is reviewed by the executive and legislative branches. South

Africa, Morocco, and Egypt have 123 Agreements with the US. South Africa is the only country on the continent to be a member of the international Nuclear Suppliers Group, which develops non-proliferation and security guidelines and standards for nuclear exporters.

Progress towards Commercial Nuclear Power

Ghana, Kenya, Namibia, Nigeria, South Africa, Sudan, Tanzania, Uganda and Zambia are the sub-Saharan African countries that have shown the most interest in new nuclear programs. The one thing almost all these countries have in common is some sort of signed agreement with an international nuclear power developer that covers various aspects of deploying nuclear power: from providing the actual technology to training local nuclear experts and setting up regulatory bodies. Russia's Rosatom is the most popular among these developers and has signed agreements with Ghana, Kenya, Nigeria, Tanzania, Uganda and Zambia. Agreements with Chinese entities such as China General Nuclear (CGN) and China National Nuclear Corporation are also common with Kenya, Sudan, Uganda, and Namibia. For now, Kenya is the only sub-Saharan country with a signed agreement for developing nuclear power with the Korea Electric Power Corporation (KEPCO). South Africa had long been developing its own reactor design, the Pebble Bed Modular Reactor, but the project stalled and funding was finally ended in 2010 (though they still retain the rights to the technology).[18] South Africa has also put out a call for bids for an additional 9.6 GW of nuclear power from Westinghouse, Areva, Rosatom, and KEPCO, although funding for that project has also stalled. Namibia's largest Uranium mine is owned and operated by China General Nuclear—almost all of the Uranium is exported to China. A CGN subsidiary, Swakop Uranium, has also submitted a proposal to build a small nuclear power plant in Namibia.[19]

This section gives a brief overview of where each of these countries stands with regards to their individual nuclear power programs.

Ghana

The choice of using SMRs as a nuclear power technology is not new to Ghana. Ramana and Agyapong (2016) argue that, as early as the 1980s, the country was interested in the 1978 200 MW Rolls Royce SMR design.[20] Additionally, in 2006, the IAEA and UN-Energy conducted a study which showed that Ghana could have a baseline of a 300 MW nuclear reactor for power purposes by 2025.[20] The actual Ghanaian government roadmap for nuclear power is to have 700 MW of capacity ready for commissioning by 2025 and later expand to 1,000 MW.[21] Ghana signed a nuclear cooperation agreement with Rosatom in 2015 to allow Ghana and Russia partner on nuclear projects, develop mutual contractual and legal frameworks for cooperation and promote Russian nuclear technology in the West African sub-region.[21]

Kenya

In 2016, Kenya underlined its goal of building 1,000 MW of nuclear power capacity by 2027 and expanding to 4,000 MW by 2030.[22] Coastal sites or sites close to major river bodies like Lakes Turkana & Victoria and the Indian Ocean were considered in a review by the IAEA in

2011. The Kenya Nuclear Electricity Board (KNEB) has signed some agreements with a few nuclear developers: one in 2015 with China General Nuclear Power (CGN), and two more with Rosatom and Korea Electric Power Corporation (KEPCO) in 2016.[21] The agreement with Rosatom was particularly wide-ranging and included collaboration beyond just building nuclear power infrastructure but also nuclear research, training experts in nuclear physics and energy, and applying radioisotopes to non-power uses in industry, agriculture and medicine.

Namibia

Namibia does not as yet have any quantifiable targets or widely publicized agreements for developing nuclear power technology. However, the government has made it clear that it plans to leverage its large uranium deposits, which constitute about 7 percent of global reserves, to produce electricity from nuclear energy technology.[21] Namibia has received a proposal from China General Nuclear to build its first nuclear power plant.[19]

Nigeria

By 2025, Nigeria aims to install 4,000 MW of nuclear capacity.[21] The Nigerian Atomic Energy Commission (NEAC) in 2010 selected four potential nuclear power sites for further evaluation. These sites were in proximity to Kogi State's Geregu/Ajaokuta, Tarabu State's Lau, Akwa Ibom State's Itu and Ondo State's Okitipupa and Agbaje.[21] A preference for the Geregu and Itu sites was declared in 2015, with Rosatom stating that it expected to build two nuclear reactors at each site.[21] The NAEC and Rosatom have signed an agreement to "prepare a comprehensive program of building nuclear power plants in Nigeria."[21] Nigeria prefers for its agreement with Rosatom to be under a Build-Own-Operate (BOO) model, with majority of equity from Rosatom.[21] Additionally, Imo State's government and the United States' Barnett Holding Co signed an agreement to evaluate potential sites in Owerri for the deployment of 5-20 MW modular reactors.[21]

South Africa

South Africa is the only African country with an operating nuclear power plant, which has been producing power since 1984. The Koeberg Power Station is about 30km northwest of Cape Town and has two units of 900MW capacity PWR reactors each.[10] The power station is owned by Eskom, South Africa's electricity public utility, and generates 5 percent of the country's electricity annually.[10] Vaalputs, is the country's low and intermediate waste disposal site, while high level waste is stored on site of the power station in pools.[10] South Africa still has plans to expand its nuclear power capacity to 9,600 MW and, apart from utilizing just the traditional nuclear technologies, is looking to explore advanced smaller modular designs too.

Sudan

Sudan's Ministry of Energy and Mines started a nuclear power program in 2007 to lay out plans to complete a nuclear power plant with either a capacity of 4,400 MW or four units of 300-660 MW by 2030.[21] A framework agreement with China National Nuclear Corporation was signed in 2016 to create a 10-year nuclear cooperation roadmap and to develop either one or two 600 MW reactors.[21]

Tanzania

Tanzania's initial plans are to build a nuclear power research reactor with the long-term goal to bring nuclear power technology to the country by 2025. This development will be done through Uranium One, which is a subsidiary of Rosatom.[23] Rosatom's activities in Tanzania are largely motivated by the country's discovery of uranium deposits and it aims to make its first production of the mineral by 2018. Uranium One has a permit to mine uranium in the Mkuju River from the Tanzanian government.[23]

Uganda

Uganda's base case scenario for nuclear power development is to have two 1,000 MW reactor units by 2031.[21] To achieve this, the Ministry of Energy and Mineral Development has signed a few agreements with some nuclear power technology developers. These agreements are the nuclear energy cooperation agreement with China Central Plains Foreign Engineering Company and the China Nuclear Manufacturing Group both in 2017, and the another with Rosatom in 2016.[23] The sites being considered for reactor deployment are in the Kyoga, Kagera and Aswa areas.[23]

Zambia

Like Namibia, Zambia does not yet have concrete numbers for its nuclear power targets. However, based on recent agreements signed with Rosatom in 2016, a tentative target of building about 2,000 MW of nuclear power capacity in the country within 10-15 years was established.[24] Additional tenets of these agreements include training Zambians in Russia to produce nuclear energy engineers and nuclear power plant staff; building a nuclear power research reactor for non-power uses such as nuclear medicine and agricultural services, including using radiation to make plant species more robust; and developing a nuclear energy regulator.[21] To manage public perception on nuclear energy technology, an agreement between Rosatom and Zambia's Ministry of Information and Broadcasting Services is centered around the production of educational material using both English and local Zambian languages.[21]

Part 2: Overview of Challenges to Deploying Nuclear Technology in Africa

A combination of several factors continue to hamper the development of the nuclear power sector in Africa. It is however worth noting that underlying all these factors is the fear that the risks associated specifically with sub-Saharan Africa are too much to bear—a sentiment common across project development in various sectors on the continent.

Usually, construction costs for nuclear power plants are exacerbated by long lead times, typically taking 5 to 10 years. In a region subject to political instability, expensive projects characterized by long construction periods are highly unattractive for investors due to the risk they carry. This has particular repercussions for financing as the heavy overnight capital costs are borne long before the plant generates revenue.[25] As such, although the life-cycle costs are competitive with fossil fuels, the lag between investment and returns is enough to deter investment. Investors will show even more reluctance to dedicate funds to large nuclear projects that cannot easily be uprooted and moved to more profitable locations, compared with smaller, less capital-intensive, more mobile fixtures. Together with the nuclear industry's track-record for exceeding projected cost and time for deploying projects,[26] the lack of administrative capacity to adequately manage projects in much of sub-Saharan Africa will amplify the uncertainties surrounding investing in nuclear on the continent—negatively impacting investment prospects.

Jewell (2011) performed an assessment of the feasibility of nuclear power development in emerging countries, and the metrics she used provide a good understanding of the obstacles that nuclear power development in Africa face. Jewell used the World Bank Government Effectiveness Indicator as a metric to measure how effective policies and regulations in each country are.[11] Many sub-Saharan African countries cannot offer a clear institutional framework complete with a distinct nuclear regulator as well as a financial framework complimented by risk and insurance provisions,[1] to pacify fears about changes in regulation during the project life-cycle while providing clarity for potential investors in understanding the magnitude of risk associated with certain projects. The lack of urgency on the part of governments to provide incentives to stimulate projects has meant that many sub-Saharan African economies continue to lag behind their counterparts in other developing regions in terms of project development.

The lack of adequate human capital and infrastructure poses a threat particularly with regards to the operation phase of completed power facilities.[1] The success of certain energy projects is highly contingent on the infrastructural ecosystem in which it finds itself. Jewell (2011) uses the electricity grid size to determine if each country investigated meets the requirement of a NPP taking up no more than 10 percent of electrical grid capacity.[11] Additionally, it is important for there to be a substantial amount of local expertise beyond the construction phase to ensure the facility is adequately maintained. But for contracts where the entity responsible for seeking finance and constructing the facility is also responsible for operating it, the presence of local know-how will be crucial, as financiers want to guarantee their return on investment. As sub-Saharan Africa is home to fewer engineers and scientists per capita, the importance of training locals cannot be disregarded.[1] The familiarity with and success of incumbent resources has also made it harder to convince local governments to diversify their resources. New energy sources are only likely to be accepted if they cost less than incumbent alternatives. It is also unlikely that establishing the necessary infrastructure alone will clear the way for new projects, as the early stages of project development tend to be the most expensive. As short-term costs can easily cloud the long-term cost benefits associated with a particular project, the idea of introducing a new, highly capital-intensive power source is likely to be met with resistance.

Safety concerns have made the idea of deploying nuclear technologies in certain locations a highly sensitive topic. A plethora of reasons—notably the political instability in certain regions (which make them susceptible to the threat of increased nuclear weapon proliferation or sabotage) and the lack of local expertise necessary to run the technological intricacies associated with nuclear plants—places sub-Saharan Africa well within the ambit of this sensitivity. In the West, notwithstanding the extensive industry know-how and the availability of in-country staffing, safety concerns have continued to encourage a move away from nuclear and toward renewable energy technologies. In Germany for instance, such events as Three Mile Island (1979), Chernobyl (1986) and Fukushima (2011) have all been cited as some of the factors motivating its *Energiewende* policy—a move toward being heavily reliant on renewable energy technologies and phasing out its nuclear power plants. In sub-Saharan Africa, where the capability to handle complex technology is currently somewhat limited, the fear of liability charges is understandable.

Regardless of the challenges that come with large energy projects, there are some models available on how the financing of NPPs could be executed well. Large hydropower plants in particular offer a good comparison to NPPs due to their similarities with nuclear in terms of scale, technological complexity, and environmental risk. There are many examples of large hydroelectric projects completed and under development across Africa. Financing options. as modeled by such large hydro projects. range from domestic government funding through taxes and government bonds (as is the case with, for instance, the Grand Ethiopian Renaissance Dam) to external sources of funding from individual countries or international organizations. Large-scale hydro projects overcame barriers of scale and long payback periods through the use of long-term finance from multilateral development banks and other external financiers. But with the World Bank and similar organizations out of any nuclear power projects, that leaves a relatively narrow set of foreign developers, like France, Russia, China, and others.

The Potential for Major Nuclear Power Vendors to Mitigate these Challenges

The costs, infrastructure, and human resource challenges of starting a commercial nuclear program can be daunting for any country, especially a developing country. With few exceptions, most newcomer nuclear countries have begun by importing a design from a foreign reactor vendor. These imports allow countries to deploy nuclear power before developing a robust domestic nuclear sector, sidestepping some of the major obstacles in the short term. Some countries then go on to develop their own domestic nuclear design, like Japan and South Korea, while others continue to operate a small number of foreign reactors like Brazil. The United States dominated the nuclear export market in the 1960s and 70s, but was soon eclipsed by Canada, Russia, and France. Many of the large nuclear vendors have shown interest in exporting to sub-Saharan African countries. The packages that these reactor vendors are offering to newcomer countries may alleviate some of the major challenges to deployment, such as financing, fuel fabrication, worker training, and waste management.

France

Although South Africa's current Koeberg nuclear power plant was built by the French company Areva, recently there have been no concrete plans to develop nuclear power between France and any sub-Saharan African country. France currently obtains some 40 percent of its uranium fuel for its domestic nuclear power generation from Niger,[27] yet the most recent report of a partnership on nuclear power in Africa was one with South Africa in 2014, which only hints at research and development and does not mention credible plans to build or export a nuclear reactor to the country.[28] France has not secured any nuclear export contracts since 2007, suggesting their high-quality (and high-cost) designs are falling out of favor. However, France was competing for a contract to build 9.6GW of new nuclear generation in South Africa, but that process has stalled.

Russia

Rosatom, a Russian state-owned company that manages its nuclear assets globally,[29] has come to dominate nuclear exports to developing countries because of their generous financing and worker training. Indeed, Rosatom is a forerunner in sub-Saharan Africa, having signed nuclear power agreements with Ghana, Kenya, Nigeria, and Uganda that cover a number of arrangements, including financing, skills development, and the actual development of nuclear power technology. The USSR also constructed research reactors in Egypt and Libya. This interest in Africa seems to only be strengthening. Even in Tanzania, there are reports that Rosatom has its subsidiary proposing the country's first nuclear research reactor.[23] Russia was also asked to bid on building 9.6GW of new nuclear in South Africa. Outside of Africa, Rosatom is about to begin its first project under its novel Build-Own-Operate (BOO) model, 4.8 GW of nuclear power in Turkey, the country's first nuclear power plant. The BOO model and Russian SMR technologies could be very attractive for African countries looking to build their first plants.

China

China completed its first nuclear export project in Pakistan in 2000 and is looking to gain a larger share in the nuclear export market, particularly in developing economies. It has recently signed significant nuclear agreements with Kenya, Sudan, and Uganda, and it appears keen on increasing its scope of nuclear influence on the African continent. In 2014, partnerships were signed between the Nuclear Energy Corporation of South Africa (Necsa) and both the China Nuclear Engineering Group and China's State Nuclear Power Technology Corporation. Both agreements were focused on training for nuclear power plant construction and NPP project management. China General Nuclear owns and operates the world's second largest uranium mine in Namibia, as well as submitting a proposal for a small nuclear power plant there.[19] China has also built research reactors in Algeria, Ghana, and Nigeria.

South Korea

Kenya for now remains the only African country to sign a major nuclear agreement with a South Korean nuclear developer, through the Korean Electric Power Corporation (KEPCO). The deal, signed in 2016, has both countries agreeing to share nuclear expertise and collaborate on the construction of nuclear power technology.[30] This is part of a wider campaign to include nuclear power in Kenya's energy mix (although South Africa also expressed interest in receiving bids from KEPCO for its nuclear expansion). South Korea is about to complete the first reactor in its first nuclear export project, a set of four reactors in the United Arab Emirates. South Korea has a reputation for completing low-cost reactors on-time and on-budget, unlike the United States and European vendors.

United States of America

The United States currently does not have any nuclear power-related projects or signed agreements for nuclear power technology deployment in Africa. However, in 2009, the US Department of Energy signed an agreement for collaboration on the research and development of advanced nuclear energy systems and reactor technology with South Africa.[31] The US company Westinghouse was invited by South Africa to submit a bid for building new nuclear there, but Westinghouse's recent bankruptcy will most likely take them out of the running. Informally, there has been interest shown by some US small and advanced nuclear power developers in potentially entering the African market.

Argentina

Argentina may not be one of the major nuclear vendors, but they do have experience supplying two research reactors in Algeria and Egypt. Additionally, their domestic CAREM reactor, a 100MW small modular reactor, could be a perfect fit for many African markets.

Canada

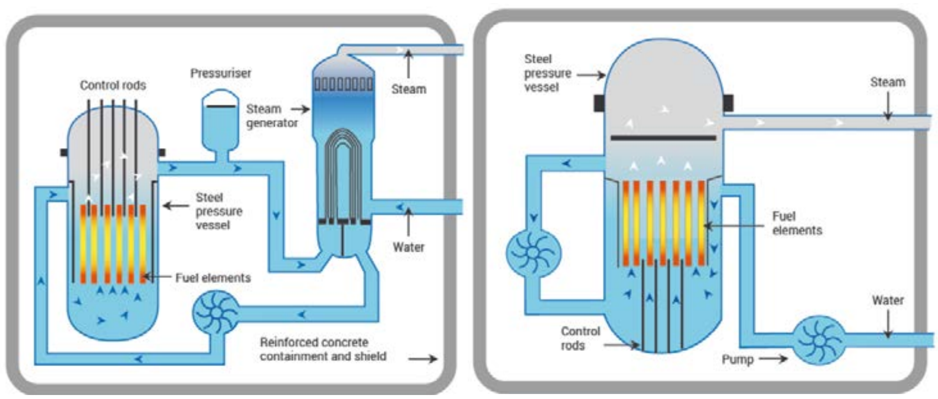
Historically, Canada dominated the export market to developing countries. Their unique heavy-water reactor runs on natural uranium, requiring less fuel-processing infrastructure. Also, their reactor's smaller size, ranging from 100MW to 700MW, made it a better fit for smaller grids. They exported reactors to India, Pakistan, Taiwan, Argentina, South Korea, Romania, and China from the 1950s through the late 1990s, but since then their exports have ceased. The decline of their domestic nuclear industry and the poor cost and performance record of the CANDU design may also be a factor.

International Finance Institutions (IFIs)

At the moment, International Finance Institutions like the World Bank and African Development Bank do not appear to have a strong interest in investing in nuclear power. In fact, most of the large IFIs have policies against investing in nuclear power projects. The challenges to developing nuclear power in Africa, mentioned earlier, could be largely the reason for this. However, it is yet to be seen if the evolving nature of nuclear power technology or any other factors could cause IFIs to develop more interest in financing NPP projects on the continent.

Part 3: The Potential of Next Generation Nuclear Technology for Africa

To appreciate the potential of next generation nuclear technology for Africa, it is useful to first understand the workings of traditional nuclear technology. To date, over 80 percent of commercial nuclear power plants have used light-water reactor (LWR) technology, which consists of two main sub-groups: the pressurized-water reactor (PWR) and the boiling-water reactor (BWR). The main difference between the PWR and BWR designs lies in where the steam used to generate electricity is generated. In the former, this steam is generated in a secondary circuit, while in the latter the steam is generated in the primary circuit, which also houses the reactor core.[32] This distinction is depicted in Figure 2 below.



(a) (b)

Figure 2. (a) Schematic of Pressurized Water Reactor (PWR) (b) Schematic of Boiling Water Reactor (BWR)[32]

Though not as widespread commercially as the LWRs, the pressurized heavy-water reactor (PHWR) is also worth mentioning. This reactor type typically utilizes natural unenriched uranium and uses heavy water, Deuterium Oxide (D_2O), as a moderator.[32] Compared to other traditional reactor designs, the PHWR is more efficient but also normally produces more fuel waste per unit output and is a proliferation concern because it converts natural uranium into weapons-grade plutionium.[32] All of Canada's 19 operating reactors are PHWRs, and they have exported their design to South Korea, China, India, Argentina, Romania and Pakistan.

For all these types of reactors, power generation can be over 1,000 MW, enough to power close to one million households in a typical Western country. Safety is managed actively with complex monitoring equipment, redundant cooling systems, and well-trained staff. LWRs require significant water for cooling, which can make siting difficult. For these reasons, traditional large-scale LWRs may not be the best first-choice for newcomer African countries.

Types of Advanced Nuclear Technology

There are a host of new and advanced nuclear technologies that have been developed or that are under current development.[33] These technologies have the potential to mitigate some of the challenges to nuclear deployment in sub-Saharan Africa. Significantly smaller and modularly built reactors could be easier to finance and faster to construct. Advanced designs could be simpler to operate, requiring fewer on-site staff, and be less prone to catastrophic accidents. Higher-temperature reactors could use significantly less water, making them a more attractive to arid and inland regions.

Small Modular Reactors (SMRs)

Small modular reactors are nuclear reactors that have nameplate capacities up to 300 MW, and that can be manufactured in a factory and transported to the power plant site for deployment using roads, railways, or barges.[34] They are typically lower cost and have shorter construction times; and due to their modularity, additional units can be added to meet demand as it increases. Their biggest advantages for African countries are their ability to be placed wherever they may be required and to supply electricity in areas without robust or sizeable grid infrastructure or capacity. Most African countries typically have grid capacities of just a few thousand megawatts, and the typical energy sector convention is that a single power plant's capacity should not exceed 10 percent of a country's total grid capacity.

SMRs can use any nuclear fuel, coolants, or fuel cycle, but those closest to deployment are advanced light-water reactors. They are designed to be more fuel efficient than the older LWRs but still utilize water as both a coolant and a moderator.[33] Either low enriched uranium-oxide or mixed-oxide plutonium and uranium fuel can be used for this design. Some passive versions of this design have the ability to autonomously cool the reactor core in the event of an emergency shutdown for at least 72 hours, and may utilize a gravity-fed coolant that allows coolant stored in a tank above the reactor, to be released in the event that the reactor coolant is lost.[33]

Many representatives from sub-Saharan African countries have expressed great interest in the potential use of SMRs but also hesitation at deploying an untested design. Thus, it would be unlikely that an African country would be the first to deploy such a design. The first commercial SMR, from NuScale Power, began the licensing process in the US in 2016 and is planning to complete their first commercial power plant in 2025.

High-Temperature Gas Reactors (HTGR)

Helium or carbon dioxide gas is used as the coolant for this technology, allowing it to operate at a much higher temperature of 1000^{o}C, achieving greater thermal efficiency.[35,36] Most notably, the reactor uses from very little to zero water, making it a good choice for inland or arid regions.[25] Most HTGR use small fuel pebbles about the size of a tennis ball, known as TRISO. This fuel is designed so that it only begins to degrade above 2000^{o}C, which is higher than temperatures attained even in an accident.[33] Typical reactor capacities range from 200 to 300 MW, and due to their low power densities, overheating is not a major concern for this reactor.[36,33] Waste fuel for this design does not need to be stored in cooling water and can be sent straight to dry storage making it well suited for dry, arid regions. China has just finished construction of a pair modular HTGRs, which will begin commercial power generation in April 2018. As China looks to grow its nuclear exports, they may start offering this reactor, especially for arid and inland regions. HTGRs are also a good source of high temperature process heat which permits them to also be used as a cogeneration plant.[37]

Pebble bed modular reactors (PBMRs) are a type of HTGR that is being developed in South Africa and is the only nuclear power technology development on the continent at the moment. The reactor type, with capacities ranging from 100 to 200 MW, utilizes helium or carbon dioxide as a coolant and graphite as a moderator and is a version of the HTGR. The developers of the PBMR describe it as a "walk-away-safe" reactor, due to its ability to shut down on its own in the event of an accident and release heat from the reactor core without a meltdown. Spent fuel from the reactor is expected to be stored on the plant site throughout its operational life and for an additional 40 years after that, before it is sent to a repository. The fuel used is not highly enriched and therefore has lower proliferation concerns. Reactor refueling also occurs while it is running, meaning less down time. Another advantage of this reactor is its relatively low requirement for highly skilled workers to operate, which could potentially be suitable for African countries that do not have access to large pools of highly skilled labor. However, PBMR development has stalled in South Africa and, after competing for a funding bid in the US, has also stalled there as well.

Floating Reactors

Floating reactor designs typically utilize the concept of a deep-sea oil platform to host a nuclear reactor, usually a small modular light-water reactor.[38] These could be ship-based like a barge. Current projects look to develop a model with a 300MW nameplate capacity.[38] The build-own-operate model could work well for this technology, where the vendor owns it and is also responsible for staffing the power plant.[39] Spent fuel is removed and stored temporarily on the plant and replaced with fresh fuel at a special handling facility.[39] The design of the technology, which places it in deep water, makes it resistant to earthquakes and tsunamis.

As floating reactors are not a new technology, they could be available for commercial use relatively quickly. Russia has been using nuclear-powered commercial shipping vessels since 1975 and has recently commissioned a new fleet.

Nuclear Batteries or Sealed Micro-Reactors

Several companies are working on extremely small modular reactors, 10 MW or less, which can operate for up to ten years without refueling. One design, Oklo, employs heat tubes to move the heat being generated to produce electricity, without the need for pumps and other moving parts, which could also help reduce capital costs, maintenance costs, and staffing.[40] In the event of an accident, the reactor is also designed to use convection to transfer heat to the ground.[40] Each unit of this reactor model will produce 2 MW of electricity and is designed to be small enough to fit into two shipping containers.[41] Owners and operators of these nuclear batteries are not meant to handle any of the fueling or maintenance aspects of operating the reactor, and they can just connect the unit to whatever system they want to provide power for until the fuel is spent. Therefore, these reactors could require minimal expertise to operate, a characteristic that would be advantageous for African countries with a low supply of skilled labor. Each unit is expected to be walk-away-safe and have a lifespan of 12 years, after which the fuel can be recycled at the central manufacturing facility to be used for another 12 years in another unit of the reactor.[41] The uranium enrichment firm Urenco is also developing a micro reactor, which produces 4 MW of electricity and 750^{o}C process heat. As none of these designs have begun the licensing process, or have plans for their first demonstrations, they will most likely not be commercially available in the next 10 years.

Non-Power Uses of Advanced Nuclear Technology

Many advanced nuclear designs are also exploring production of services beyond just electricity. While these additional services, like desalination or industrial heat, may not make the plant cheaper they could add significant value that might make the project more economic on the whole. Many of the advanced nuclear designs operate at extremely high temperatures which allows them to produce high-temperature process heat which could be applied to the following uses:[33,42]

- Seawater desalination
- Industrial processes such as chemical & fertilizer production
- Oil Refining
- District Heating

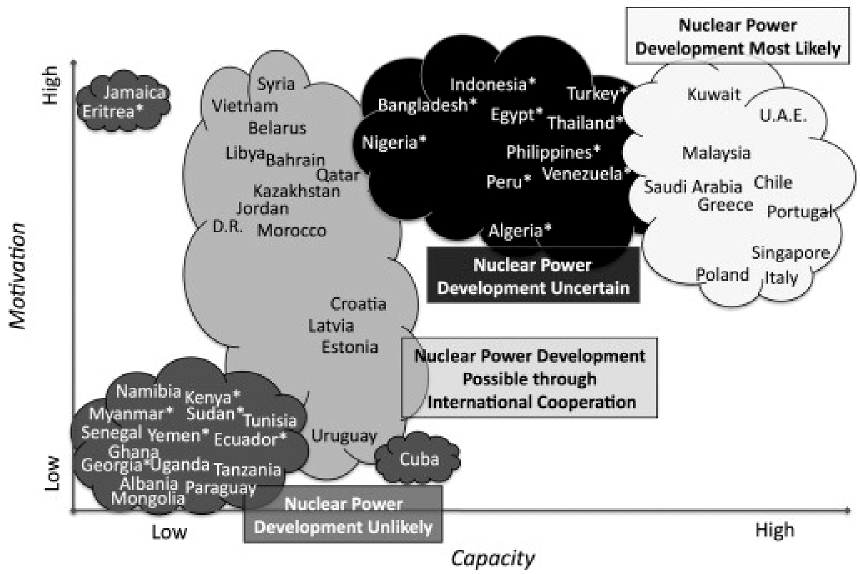
Such non-electric uses for nuclear power may make the technology attractive for off-grid mining operations, large factories, or water-starved cities. These first users might be willing to pay more for the non-electric services and accelerate the deployment of nuclear technology for electricity production as well.

Several nuclear desalination plants have operated in Kazakhstan and Japan, with several more in development in Argentina, India, Pakistan, and China.[43] The Korean SMR under development, called SMART, produces up to 100 MW of electricity along with 40,000 m^3 (~10 million gallons) of potable water every day.[44]

How Advanced Nuclear Technology Can Address Challenges to Deployment

The analysis by Jewell (2011) discussed in Part 2, which considered the potential of the development of nuclear power in a number of countries, concluded that almost all the African countries analyzed were unlikely to develop nuclear power in the foreseeable future (see Figure 3 below). Even for Nigeria, where Jewell showed motivation to be high, nuclear power development was deemed to be uncertain. Jewell's assessment criteria for determining capacity included current and projected grid capacity, GDP and GDP/capita, Government Effectiveness Indicator (GEI) and Political Stability Indicator (PSI) by the World Bank and Political Instability Task Force (PITF).[11] Motivation was determined by the magnitude and average demand growth rate of electricity consumption, and import dependency and diversity of the primary electricity sources.[11]

Figure 3. Jewell (2011) assessment of potential of nuclear development in Africa[11]



Maybe most important for this discussion, Jewell's analysis was based on the development of conventional, large light-water reactors with capacities exceeding 1,000 MW.[11] Building upon Jewell's analysis, we look at the potential for small and advanced nuclear technologies to increase the likelihood of nuclear power development in Africa. To fill this gap, we generated an analogous representation (Figure 4), which charts the capacity and motivation of our focal countries for the development of small and advanced nuclear reactors. Motivation was largely based on how far each country had gone in signing agreements with nuclear developers to develop some sort of nuclear power capacity in the next few years. Capacity was based on the energy and economic statistics highlighted for each country (summarized in Table 3 below). For example, while only South Africa's grid could handle a 1 GW reactor under the 10 percent rule-of-thumb, all but Uganda could handle a 100 MW SMR.

Though not based on hard categorization and ranking of each criterion for each country, as was done in Jewell (2011), the main aim of our analysis is to show that adopting small and advanced nuclear technology in Africa could increase the feasibility of development of nuclear power by lowering the infrastructural and institutional barriers for some capacities. Using these small and advanced technologies, the potential for nuclear power development on the continent could fall anywhere from very likely (as is the case with South Africa and Nigeria) to requiring more rigorous financing and infrastructure support for development to be feasible (as is the case with Uganda).

Figure 4. Potential of nuclear power development in Africa, using small and advanced nuclear technologies

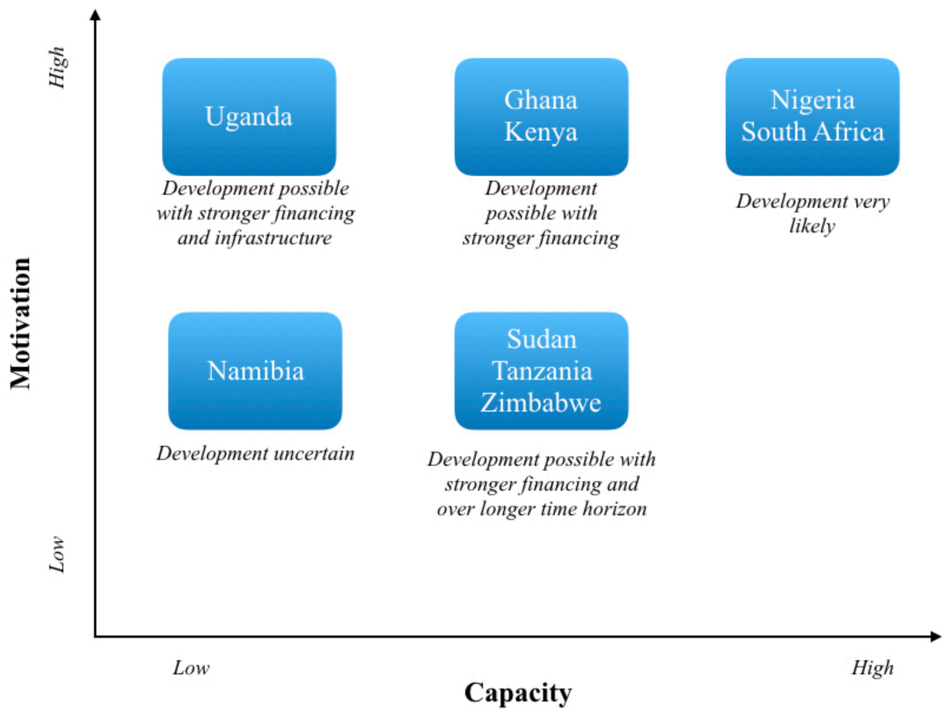


Table 3. Summary of economic and energy statistics for each country analyzed. Data from same year, except where specified: ⌘ data from 2015, * data from 2016

	Ghana	Kenya	Namibia	Nigeria	South Africa	Sudan	Tanzania	Uganda	Zambia
2016 GDP ($ Billion)	43	71	10	405	295	96	47	26	20
2016 GDP Per Capita ($)	1,514	1,455	4,141	2,178	5,274	2,415	879	615	1,178
2022 GDP Growth (%), IMF Projection	5.4	6.5	3.6	1.7	2.2	3.5	6.6	7.3	4.5
2015 Energy Consumption (Mtoe)	7	3	1	16	122	5	3	3	2
2015 Electricity Consumption (TWh)	10	9	4*	26	243	1	6	2	11*
2017 Grid Capacity (GW)	3⌘	1.5	1.1	6.5	43.6	3.2*	1.5*	0.8⌘	2.8*
2014 Electrification Rate (%)	78	36	50	58	86	45	16	20	28

Conclusion

Even compared with other newcomer nuclear countries, it is clear that no sub-Saharan African country is ready to build its first commercial nuclear power plant in the next five years. Even in South Africa, which already has commercial nuclear power, plans to build an additional 9.6 GW of nuclear have stalled over questions of financing.

Nonetheless, we need to recognize that there is great interest and demand for nuclear across the African continent, and nuclear vendors are keenly aware of this. Competition among the major vendors—Russia, China, and South Korea—may also accelerate deployment by lowering costs and providing more services within the scope of the project. Dozens of Nuclear Cooperation Agreements and Memoranda of Understanding have been signed with these countries, ranging from research and development and human resources development to full reactor projects. Such agreements will only continue to expand and grow in value.

Critically, we must consider how technological advances in nuclear power may change what is feasible in Africa. New reactor designs that are smaller, simpler, and safer may accelerate the deployment of commercial nuclear in these sub-Saharan countries. And new business models such as Build-Own-Operate, offshore nuclear, or vendor-financed projects, may help leapfrog limited state capabilities. Small modular reactors could lower the barrier for grid capabilities, allowing smaller countries access to nuclear. And the Build-Own-Operate model popularized by Rosatom could help countries overcome the financial, human capital, and regulatory obstacles of their first plants. Still, nothing can circumvent the need for a robust safety and security regulator, nor the transparency and safeguards set in place by the International Atomic Energy Agency.

In the short-term, we expect to see more progress on regulatory and infrastructure milestones. Countries will likely sign many more MOUs and NCAs with major reactor vendor countries such as Russia, China, and South Korea. In the longer term, we expect one to five countries in Africa to begin commercial nuclear programs, most with the help of a foreign reactor vendor.

Given the key role that energy plays in advancing human development, what role does the development community play in the nuclear space? We have seen that the major development banks have prohibited investments and often even conversation around nuclear power. But as they also phase out investment in fossil fuels, and as concern around climate change grows, they should consider relaxing these restrictions. More importantly, nuclear development in sub-Saharan countries is currently dominated by foreign companies, which may not always have the interests of the host country as a priority, although their investment role is critical. Therefore, the development community is greatly needed in facilitating these challenging conversations around transparency, equity, good governance, and human capital. There is more work to be done in convening workshops across these countries to standardize norms and best practices around emerging nuclear technologies. Finally, there is a critical need for independent voices to educate and engage with potential host communities around the benefits—as well as the real risks—of nuclear power, such that host communities know their rights and are empowered to negotiate fair contracts for potential nuclear power facilities in their backyard.

References

1. Kenny, A. Prospects for nuclear power in Sub-Saharan Africa in the 21st century. *Int. J. Glob. Energy Issues* **30,** 177 (2008).
2. Kawanami, T. Africa needs $90bn for infrastructure, World Bank chief says. *Nikkei Asian Review* (2016).
3. Ernst and Young. Addressing Africa's infrastructure deficit. (2017). Available at: http://www.ey.com/gl/en/industries/government---public-sector/dynamics---collaborating-for-growth_addressing-africas-infrastructure-deficit.
4. Eberhard, A., Gratwick, K., Morella, E. & Antmann, P. *Independent Power Projects in Sub-Saharan Africa: Lessons from Five Key Countries*. *Directions in Development - Energy and Mining* (2016). doi:doi:10.1596/978-1-4648-0800-5
5. International Energy Agency (IEA). Africa Energy Outlook: A Focus on Prospects in Sub-Saharan Africa. 1–242 (2014).
6. Africa's Population Boom: Will It Mean Disaster or Economic and Human Development Gains? *The World Bank* (2015). Available at: http://www.worldbank.org/en/region/afr/publication/africas-demographic-transition.
7. IAEA. IAEA Meeting: African Countries Agree to Cooperate on Nuclear Power Development. (2015). Available at: https://www.iaea.org/NuclearPower/News/2015/2015-07-20-nids.html.
8. Campbell, K. Interest in nuclear energy said to be rising across sub-Saharan Africa. *Engineering News* (2017).
9. Jewell, J. A nuclear-powered North Africa: Just a desert mirage or is there something on the horizon? *Energy Policy* **39,** 4445–4457 (2011).
10. Eskom. Koeberg Power Station. (2016). Available at: http://www.eskom.co.za/Whatweredoing/ElectricityGeneration/KoebergNuclearPowerStation/Pages/Koeberg_Power_Station.aspx.
11. Jewell, J. Ready for nuclear energy?: An assessment of capacities and motivations for launching new national nuclear power programs. *Energy Policy* **39,** 1041–1055 (2011).
12. IAEA. *Research Reactors in Africa*. (2011).
13. Lawal, D. UNIPORT graduates Nigeria's first nuclear engineers. *The Scoop* (2014).
14. Waruru, M. Russia courts Africa with nuclear science scholarships through Rosatom. *The Pie News* (2017).
15. IAEA. Milestones in the Development of a National Infrastructure for Nuclear Power. *IAEA Nucl. Energy Ser.* **NG-G-3.1,**
16. Ghana completes first phase of Nuclear Power Programme. (2017). Available at: http://www.ghana.gov.gh/index.php/media-center/news/3356-ghana-completes-first-phase-of-nuclear-power-programme. (Accessed: 27th September 2017)
17. Gil, L. Nigeria to Prepare for Nuclear Power Programme: IAEA Director General Visits Abuja. (2016). Available at: https://www.iaea.org/newscenter/news/nigeria-to-prepare-for-nuclear-power-programme-iaea-director-general-visits-abuja. (Accessed: 27th September 2017)
18. World Nuclear Association. Nuclear Power in South Africa. (2017). Available at: http://www.world-nuclear.org/information-library/country-profiles/countries-o-s/south-africa.aspx. (Accessed: 1st January 2017)

19. Larmer, B. Is China the World's New Colonial Power? *New York Times* (2017).
20. Ramana, M. V. & Agyapong, P. Thinking big? Ghana, small reactors, and nuclear power. *Energy Res. Soc. Sci.* **21,** 101–113 (2016).
21. World Nuclear Association. Emerging Nuclear Energy Countries. (2017).
22. Ministry of Energy and Petroleum. Nuclear Energy Power Programme. (2016).
23. Tanzania: Russian Firm to Build Nuclear Reactor in Tanzania. *The East African* (2016).
24. Lusaka Times. Zambia plans to go to nuclear to end loadshedding. (2016).
25. Kessides, I. N. & Kuznetsov, V. Small modular reactors for enhancing energy security in developing countries. *Sustainability* **4,** 1806–1832 (2012).
26. Sovacool, B. K., Gilbert, A. & Nugent, D. An international comparative assessment of construction cost overruns for electricity infrastructure. *Energy Res. Soc. Sci.* **3,** 152–160 (2014).
27. Hughes, M. France More Worried about Niger's Uranium Than its People | HuffPost. *Huffington Post* Available at: https://www.huffingtonpost.com/michael-hughes/france-more-worried-about_b_470217.html. (Accessed: 1st January 2017)
28. South Africa and France sign nuclear accord. *World Nuclear Association* (2014). Available at: http://www.world-nuclear-news.org/NN-South_Africa_and_France_sign_nuclear_accord-1410147.html. (Accessed: 1st January 2017)
29. About Us. *Rosatom* Available at: http://www.rosatom.ru/en/about-us/.
30. South Korea, Kenya to cooperate on nuclear energy. *Reuters* (2016).
31. US DOE. United States and South Africa Sign Agreement on Cooperation in Nuclear Energy Research and Development. *Department of Energy* (2009). Available at: https://energy.gov/articles/united-states-and-south-africa-sign-agreement-cooperation-nuclear-energy-research-and.
32. World Nuclear Association. Nuclear Power Reactors. (2017). Available at: http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/nuclear-power-reactors.aspx.
33. Nordhaus, T., Lovering, J. & Shellenberger, M. *How to Make Nuclear Cheap.* (2013).
34. Bowen, M. *Enabling Nuclear Innovation: Leading On SMRs.* (2017).
35. Makhijani, A. The Pebble Bed Modular Reactor. (2012).
36. Kessides, I. N. The future of the nuclear industry reconsidered: Risks, uncertainties, and continued promise. *Energy Policy* **48,** 185–208 (2012).
37. PBMR. PBMR - Technology. (2017). Available at: http://www.pbmr.com/index2.asp?Content=182. (Accessed: 1st January 2017)
38. Stauffer, N. W. A new look for nuclear power. *MIT Energy Initiative* (2015). Available at: http://energy.mit.edu/news/a-new-look-for-nuclear-power/.
39. Prasad, S., Abdulla, A., Granger Morgan, M., Es, I. & Azevedo, L. Nonproliferation improvements and challenges presented by small modular reactors. *Prog. Nucl. Energy* **80,** 102–109 (2015).
40. LaMonica, M. UPower's Truck-Size Nuclear Power Plant. *IEEE Specturm* (2014).
41. Russell, K. YC-Backed UPower Is Building Nuclear Batteries. *TechCrunch* (2014).
42. Advanced Applications of Water Cooled Nuclear Power Plants. (2007).

43. Ahmed, S. A., Hani, H. A., Al Bazedi, G. A., El-Sayed, M. M. H. & Abulnour, A. M. G. Small/medium nuclear reactors for potential desalination applications: Mini review. *Korean J. Chem. Eng.* **31,** 924–929 (2014).
44. Khamis, I. A global overview on nuclear desalination. *Int. J. Nucl. Desalin.* **3,** 311–328 (2009).