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Thinking big? Ghana, small reactors, and nuclear power

M.V. Ramana*, Priscilla Agyapong

Nuclear Futures Laboratory and Program on Science and Global Security, Princeton University, United States

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ABSTRACT

Ghana has been seen as a potential market for small nuclear reactors and Ghanaian nuclear officials have, on occasion, expressed an interest in such reactors. However, Ghana seems to be heading towards procuring a reactor from Russia with a capacity of 1000–1200 MW. A power plant with such a large power generation capacity is not appropriate to Ghana's limited electricity grid or its financial circumstances. This paper examines the likely reasons for this focus and argues that despite greater government interest in setting up nuclear reactors, Ghana's nuclear establishment may not have the political clout to force through the purchase of a reactor, and has therefore attempted to position itself as a complete, one-stop solution to Ghana's electricity crisis, by calling for the construction of just one or two large nuclear power plants. The paper draws on the role of discursive elements in energy policy making, discusses the policy implications of this reactor choice, and offers evidence for the proposition that decision about nuclear power are not made on the basis of merely techno-economic considerations but are driven by a range of social and political factors.

1. Introduction

In August 2015, the Ghana Atomic Energy Commission (GAEC) signed a Memorandum of Agreement with the State Atomic Energy Corporation of the Federation of Russia (Rosatom) for the construction of a Nuclear Power Plant in Ghana [1]. According to Ghana's Minister for the Environment, Science, Technology and Innovation, the agreement provides for the purchase of Russian design power units of 1000–1200 megawatt (MW) capacity as well as the training of staff and establishment of necessary nuclear infrastructure [1].[1]

Ghana's plans to set up a nuclear power plant are part of a trend involving multiple countries in Africa that are considering nuclear power. In July 2015, for example, representatives of ten African countries formed the African Network for Enhancing Nuclear Power Programme Development (ANENP) [2]. A common justification offered for these nuclear plans is the fact that a very large number of people in the region do not have access to electricity. The International Energy Agency (IEA) in 2012 estimated that Sub-Saharan Africa has "more than 620 million people, nearly half of the global total" that do not have access to electricity [3]. In the last decade, energy access has grown increasingly as a focus of social and economic policy for national governments across the sub-continent and for developmental partners like the African Development Bank, World Bank, and African Union. During the same period, scholars have analyzed requirements for an energy transition in Africa [4]. This is the context in which plans for nuclear power are being made.

Given this milieu, Ghana's nuclear power plans are not surprising. And yet, GAEC's preference for a reactor with 1000 MW or more of generation capacity, assuming it is implemented, does raise a puzzle. As of 2015, Ghana's total installed electricity generation capacity is only 2831 MW [5]. Installing even one 1000 MW reactor within such a small grid would create instabilities in the operation of the national electrical system. Surely, energy planners must be aware of this mismatch. Indeed, as late as 2008, Ghanaian officials stressed "suitability to the Ghanaian and West African grid size" as an important criterion in choosing a reactor [6]. Why, then, is Ghana considering the purchase of such a large reactor?

The puzzle is even greater in light of the extensive promotion and marketing of small nuclear reactors (with power levels of 300 MW or smaller) that the nuclear industry has engaged in over the last decade. Given their smaller power output, such reactors would be a better fit to Ghana's grid. Further, as described below, Ghana has been viewed for decades as a likely customer for such reactors, both because of its long-expressed interest in acquiring nuclear power plants and because of its technical and financial constraints. Thus, Ghana offers a good case study to test the idea that

* Corresponding author.
E-mail addresses: ramana@princeton.edu (M.V. Ramana), priscillaboakye@alumni.princeton.edu (P. Agyapong).

[1] All use of MW refers only to MWe (megawatt electric) in this paper.

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small developing countries that are interested in nuclear power will acquire small reactors.

As we argue below, Ghana's preference for large reactors has much to do with the narrative put out by the Ghana Atomic Energy Commission about the potential for nuclear energy to solve the country's energy shortages by constructing just one or two plants. Although the decision does not make sense from the view point of electric grid management, Ghana's choice of a Russian reactor offers further evidence for the proposition that decisions about nuclear power are not made on the basis of merely techno-economic considerations but are driven by a range of social and political factors [7–12].

This paper starts with a short literature review followed by sections that lay out the electricity profile of Ghana and recount the history of Ghana's efforts to set up a nuclear program. This is followed by examining the factors that lead to the expectation that Ghana would purchase a reactor with relatively low levels of power, roughly in the few hundred megawatt range. Next, we describe the constraints on Ghana's nuclear reactor choices, followed by a discussion of the strategies adopted by GAEC and Russia, which is likely to be invited to supply the first nuclear plant, to overcome these constraints. Before concluding, we offer our main argument about why GAEC prefers a large reactor to a small one.

2. Discursive elements

Over the last couple of decades, there has been increasing attention paid to the role of discursive elements such as narratives, fantasies, imaginaries and stories in energy and environmental policy making. Scholars have applied such methods to settings as varied as Russia's extraction and exporting of hydrocarbons [13]; energy efficiency in buildings [14]; the Desertec project for concentrating solar power in the Sahara Desert [15]; electricity rate setting in the state of Illinois [16]; the diffusion of photovoltaic technology in Ontario, Canada [17]; energy transitions in general [18,19]; and the idea of an economy based on hydrogen energy [20–22]. These are just a few examples, but they serve to reinforce the importance of examining how discursive elements can shape energy policies and energy politics.

Coming specifically to nuclear energy, Sheila Jasanoff and Sang-Hyun Kim have explored the role of "national sociotechnical imaginaries" which they define as "collectively imagined forms of social life and social order reflected in the design and fulfillment of nation-specific scientific and/or technological projects" in shaping the trajectories of nuclear power in the United States and South Korea [23,24]. John Proops has sought to explain the growth of nuclear power despite its uneconomic nature by tracing it to the close match between the discourse of the modernizing and interventionist state and the discourse of nuclear power, as offering control and modernity [25]. Geels and Verhees have addressed the role of cultural legitimacy in shaping Dutch nuclear energy policy [26]. Jonas Anshelm has documented the turn to magical and mythical metaphors utilized in establishing the Swedish nuclear program [27].

Discussions of nuclear power by its proponents have largely focused on the future in preference to the present or the past [28–30]. This focus allows nuclear advocates to paint a glorious prospect of a country with no shortages of electricity, ignoring all the problems associated with setting up nuclear reactors. But there are other features that mark discussions about nuclear energy, and, because of the intimate relationship between the two, nuclear weapons. Analyzing nuclear history in the United States, William Kinsella has identified four key themes that characterize nuclear discourse: secrecy, mystery, potency, and entelechy. Of these, Kinsella points out, entelechy – a philosophical concept that refers to that which realizes or makes actual what is otherwise merely potential – is a key rhetorical resource that can motivate "action toward certain outcomes rather than others" [31].

This literature suggests many insights, three of which are important for our purposes. First, and most obvious, a variety of actors – governments, bureaucracies and individuals (for example, scientists and technologists) – do use discursive elements to further their goals. Although these are not always successful, the fact that they do work in some cases results in other actors attempting similar narratives. Thus, it should not be surprising that Ghanaian nuclear technologists would resort to such a strategy. Second, the discursive elements that are deployed and the expectations that underlie them are biased by the concerns of the time and demonstrate "functional thinking" in targeting the fulfillment of some perceived social need [32]. As we shall see, in Ghana's case the major concern that the nuclear establishment has targeted is the shortfall in energy.

Third, especially when it comes to technologies, the discursive elements employed often portray technologies as capable of creating a desirable society. As Frank Laird suggested through his examination of the advocacy of solar and wind energy technologies in the United States, these advocates believed that "creating new technological systems would eventually bring about the society they wanted" [33]. Advocates of these technologies routinely exaggerate potential benefits and downplay risks [32,34]. In the context of nuclear power, Paul Josephson has explained how the technological utopianism of Russia's political and scientific leaders has led them to endorse an ambitious program of nuclear reactor construction without adequate controls or public involvement and one that comes with the "potential for significant human and environmental cost should there be a mishap" [35]. Likewise, Ghana's nuclear establishment, as we document below, has underestimated the economic costs of, and the financial risk associated with, nuclear power.

3. Ghana's power profile

Across Sub-Saharan Africa, Ghana has produced one of the greatest success stories in energy access expansion. Aggressive efforts in the last two decades have resulted in 72% of the population being connected to electricity; in comparison, the regional average of national electrification rates stands at 32% [3].

Yet over the last two decades, power supply to consumers in Ghana has become more unreliable. Since the year 2000, the country has experienced at least three major power crises: first in 2002, followed by another in 2006–2007, and the crisis that began in 2013 and has continued till the time of this writing [36]. In early 2015 the Volta River Authority, Ghana's parastatal generation company, announced it was shutting down the third of six turbines at the 1020 MW Akosombo hydroelectric plant due to low water levels. Efforts to address the shortage through the use of floating emergency plants may not entirely resolve the power problems in Ghana because natural gas supplies have not been reliable or affordable. Domestic gas production has been challenged by technical and financial deficiencies [37]. The systemic nature of the crisis in the electricity system is paralleled in the area of oil-based energy, which has been described by scholar Franklin Obeng-Odoom in this journal [38].

Along with these supply challenges, government projections made in 2013 suggest an additional 4000 MW will be required over the next 20 years to sustain economic growth. The government has responded, inter alia, by announcing that it would increase installed capacity to 5000 MW by the end of 2016, setting a goal of 10% renewables in the generation mix by 2020 [39], and expanding capacity at existing gas plants. The government has also plans to use a combination of energy efficient technologies (LED lights, for example) and demand shifting to reduce peak demand [40]. If these plans materialize, the power crisis would be substantially mitigated. Further, as we have shown in the Appendix, solar photovoltaic energy and natural gas are likely to be the most economical ways of generating more electricity.

In line with the state's goal of diversifying and increasing installed capacity, there is evidence of significant efforts being made to advance solar power and strengthen natural gas based generation. Apart from their relative economic attractiveness, both these forms of power can also be set up in a modular fashion, with modest increments in generation capacity to match increases in demand. The more conventional response in Ghana has been to focus on expanding natural gas based generation and the country is set to start importing Liquefied Natural Gas (LNG) by 2017 [41]. But the longer-term energy future for Ghana could well involve a significant expansion of solar energy. Its largest solar plant (20 MW capacity) was connected to the grid in April 2016 [42] and the even larger Nzema solar power plant (155 MW capacity), which would likely become Africa's largest solar installation, is under construction [43]. In principle, solar power offers the potential to meet all of Ghana's electricity needs; one United Nations Environment Programme study from 2015 found that just "10 per cent of lands in the northern regions that are within 20 km of transmission infrastructure. . .after having eliminated the lands that are already in use for competing purposes such as agriculture and protected areas. . .could theoretically [support] an installed capacity of 106 GWp" [44]. This is in the scenario with the lowest solar energy generation and other scenarios envision more than four times the solar capacity; even in the limited scenario, solar photovoltaics could constitute about thirty times the currently installed electricity generation capacity. Thus, focusing on an expansion of solar energy does offer a sound strategy for Ghana to address its current and future electricity requirements.

Nevertheless, the current power crises and projected demand of 4000 MW have created the space for Ghana's nuclear establishment to advance itself as the dominant, if not the sole, solution to the problem of electricity shortages. Institutions, of course, regularly use real or perceived needs to offer their product as the appropriate solution.[2] As we shall see below, GAEC has certainly adopted that strategy. Before getting into the details of this strategy, we outline the history of Ghana's nuclear energy program and its reactor choices.

4. Ghana and nuclear energy: a historical overview

Ghana's interest in nuclear energy dates back to its formation as a modern state. Kwame Nkrumah, the country's first president, sought an industrialized future led by large scale energy production, most spectacularly through the construction of the Akosombo dam on the Volta river [48]. Ghana joined the International Atomic Energy Agency (IAEA) in 1959, only two years after its independence in 1957 [49]. The Ghana Atomic Energy Committee was set up in 1961 and this was replaced by the Ghana Atomic Energy Commission (GAEC) in 1963 [49]. GAEC's mandate was to promote and develop the application of nuclear technology for peaceful socioeconomic advancement.

In the beginning, everything seemed to be going well for GAEC. The following year saw the inauguration of the Kwabenya project, whose plans included the construction of a 2 MW Soviet research reactor and the training of nuclear scientists and technicians [6]. Speaking at the inauguration of the Ghana Atomic Reactor Project, Nkrumah laid out a compelling vision for the future of atomic energy: ". . . We have therefore been compelled to enter the field of Atomic energy, because this already promises to yield the greatest economic source of power since the beginning of man. Our success in this field would enable us to solve the many sided problems which face us in all the spheres of our development in Ghana and in Africa" [50]. While subsequent history has shown that nuclear power is anything but an "economic source" of generating electricity, the statement is quoted repeatedly in all official accounts of Ghanaian nuclear history with no trace of irony.

In this period of political commitment to the nuclear project, many Ghanaian students were sent overseas (mainly to the Soviet Union) to study in nuclear energy programs. In 1964, Nkrumah expected that the young men and women "who have received their specialist training in the Soviet Union and elsewhere would provide the basis for our corps of skilled specialist in nuclear science. We are sending more Ghanaians abroad to acquire this specialist knowledge in training" [51]. Because of bilateral agreements with the Soviet Union, several Soviet experts and technicians came to Ghana to lead the initial stages of construction [52].

By 1966, the reactor's construction had reached an advanced stage and it was scheduled to be completed by the year's end [52]. But all of this progress came to a halt after February 24, 1966 when Nkrumah was overthrown in a coup reportedly backed by the U.S. Central Intelligence Agency [53,54]. The nuclear project was disbanded, scholarships to Ghanaian students abroad were discontinued, and Soviet workers and experts who had been brought in to develop the infrastructure were deported. This coup and the following three decades of political instability eroded Ghana's capacity to further its nuclear plans.

The new government, the National Liberation Council (NLC), set up a committee under Sir John Cockcroft, a British Nobel laureate physicist, to examine the credibility and necessity of Nkrumah's nuclear ambitions. The resulting recommendation was that Ghana would not need nuclear power for another 20 years [52]. The new government, already mistrusting Nkrumah's nuclear agenda, used Cockcroft's analysis to completely discontinue the Kwabenya project.

The following two decades were unstable ones for the nuclear power in Ghana. During the Second Republic, Ghana had three presidents who all served for short periods of time. Starting in 1973, there was a brief renewal of interest in nuclear power after another military coup ended the Second Republic and established the National Redemption Council (NRC) in 1972 [55]. A management committee and Reactor Technical committee were created to reactivate the Kwabenya project. Efforts were made to obtain a 1 MW reactor from Frankfurt University, Germany [49]. Arrangement toward the reactor's shipment to Ghana were all but finalized when a subsequent coup in June 1979 caused the German government to annul all arrangements [52]. The result of this uncertainty was that overall government interest in nuclear energy diminished until the 1990s; there was also what the IAEA describes as a mass "exodus of the core of the country's nuclear experts" [49].

In 1994 following a transition to democratic rule, Ghana entered into an agreement with the People's Republic of China to purchase a 30 kW research reactor [49]. Commissioned in March 1995, the reactor is fueled with highly enriched uranium and uses metallic beryllium as a reflector for neutrons, with light water as moderator and coolant [56]. Although the reactor has been used extensively for research and training nuclear scientists, it has not provided Ghana with any experience in operating a power reactor. Apart from the acquisition of this research reactor, nuclear power plans were mostly dormant during the 1980s and 1990s. It was only after the power crisis in 2006-7 that the pace of progress quickened.

[2] There is a vast literature on bureaucratic politics although very little of that is focused on nuclear power. However, a closely associated arena wherein nuclear technology has been examined through a bureaucratic and institutional lens is the acquisition of nuclear weapons [45–47].

In May 2007, the governing New Patriotic Party set up the Nuclear Power Committee to assess the viability of, and develop an implementation roadmap for, nuclear generation. The resulting roadmap recommended a Presidential Commission on Nuclear Power Development and a nuclear capacity target of 400 MW by 2018, which was approved by the Cabinet [6].

Matters slowed down initially with the National Democratic Congress party coming to power after the 2008 elections. But in April 2011, seven working groups were established to assist in various aspects of planning for the country's nuclear power program. In addition, the President created a nuclear power directorate at the Ministry of Energy and Petroleum and inaugurated the Nuclear Energy Program Implementation Organization (NEPIO)—both in 2012. All of this culminated in July 2015 when Ghana's parliament approved the Nuclear Regulatory bill, which seeks to establish a Nuclear Regulatory Authority to carry out regulation of nuclear activities [57].

This long history offers three lessons. First, decisions to acquire a nuclear power plant appear to be tentative and reversible with each successive political regime. This trend has not been the case in the last decade, and there has been bipartisan support for the nuclear program, but it is not clear if this support will be sustained for a period of 15–20 years, the time it will take to successfully commission the first nuclear power plant. Second, the GAEC does not have the clout and autonomy to force a reactor purchase through an unwilling leadership. It should not be surprising that GAEC has been making strong arguments for the construction of nuclear power plants for decades. However, any movement towards that goal has occurred only during administrations that were themselves favorable towards nuclear power. Third, and more generally, the failure of Ghana to establish nuclear power so far offers evidence for the proposition offered by energy analyst Jessica Jewell in 2011 that for nuclear power to be implemented, "a country must have a sufficient institutional capacity and political stability to safely manage the nuclear power program, gather international support, and attract, where necessary, private investment" [58]. More recently, Jewell and Seyithan Ahmet Ates have identified "Financial capacity", "Institutional capacity to attract investment and manage a nuclear power program", "Technical capacity to integrate in grid", "Human resource capacity to run program", and "State capacity for economic and energy planning" as necessarily factors to explain why a country is "succeeding or failing in its pursuit of nuclear power" [59]. The history discussed so far shows that one or more factors have been absent during each of the phases when nuclear power was seriously pursued in Ghana.

More generally, Ghana illustrates the general proposition that nuclear trajectories are rarely, if ever, deterministic. Many developing countries – Indonesia, Philippines, and Egypt – have long established atomic energy commissions, but their plans for building nuclear power plants have been unrequited. In this sense, the history of nuclear power in Ghana is similar to the case of Thailand where scholar Itty Abraham found that "the impact of heterogeneous exogenous factors" have for decades blocked efforts by "successive organizations heading the Thai nuclear program" to get a power reactor off the ground [60].

Despite this history and the multiple constraints confronting Ghana, if one assumes that a nuclear reactor is going to be purchased this time around, one may ask what kind of reactor that will be? Until the recent agreement with Russia was signed, there were many indications that suggested that the preferred option might be a small reactor with a power capacity of a few hundred megawatts. Below we describe these factors and the broader economic parameters that govern Ghana's reactor choices.

5. Small reactors and Ghana

The nuclear industry has long offered a vision of powering developing countries with atomic plants. From the very early years, this vision involved the use of small reactors. At the 1955 Geneva conference, for example, the Department of Economic and Social Affairs of the United Nations argued:

> "The present volume of energy consumption in most underdeveloped countries, however, does not justify the employment of large thermal power stations and the same will be true, in many cases, of large-size reactors. In other words, nuclear power in underdeveloped countries would have to be generated in plants with a relatively small capacity. In many cases reactors would have to compete with scattered diesel units" [61].

Sixty years after the Geneva conference, advocates for expanding nuclear power in developing countries continue to push the same idea, with the only difference being that the definition of small has increased to power outputs up to 300 MW [62–65]. The nuclear industry, especially in the United States, also prefers to include the term modular to allude to the idea that these reactor components would be manufactured in the factory and assembled at the actual site of the power plant.

Such Small Modular Reactors (SMRs) have gained visibility in public discourse in various countries. The acronym SMR is also used, especially by the IAEA, for the related category of "Small and Medium Reactors", where medium refers to reactors with outputs between 300 and 700 MW. According to officials from the Department of Nuclear Energy of the IAEA, "SMRs may provide an attractive and affordable nuclear power option for developing countries with small electrical grids and limited investment capability" [66]. The same point is echoed by an analyst from the World Bank for the specific case of Africa: "SMRs could provide an attractive and affordable nuclear power option for many African countries with small electricity markets, insufficient grid capacity, and limited financial resources" [67].

Among African countries, Ghana has been considered a particularly promising customer for SMRs [68,69]. According to the IAEA's projections published in 1974, Ghana was estimated to have a potential market for four SMRs, of 150 MWe each, to be constructed between 1980 and 1989 [70]. In a 2006 study carried out by UN-ENERGY, a United Nations interagency mechanism, along with the IAEA, the baseline scenario of energy generation in Ghana posited one small 300 MW reactor being operational by 2025 [71].

In 2011, the U.S. Department of Commerce's International Trade Administration identified twenty seven countries as "markets of interest for new nuclear expansion", rating them on how closely they matched seven features of a potential SMR market; among them was Ghana, which was rated more highly than other African countries like Nigeria, Kenya, and Egypt [72].[3] A group of academic researchers used eight strategic scenarios that determined the conditions under which SMRs would have a competitive advantage in a country in comparison to large reactors and identified Ghana as the only country that had two specific factors favoring SMRs: "smaller utilities with low capitalization" and "distributed or remote communities" [73]. In 2013, an IAEA official listed Ghana as one of the "new entrants with active participation in IAEA's programme on SMR" [74].

For its part, the Ghanaian nuclear establishment has also expressed an interest in SMRs. In the early 1980s, Ghana was report-

[3] The seven criteria used are: (a) low population density, (b) anticipated population growth, (c) anticipated carbon emissions growth, (d) anticipated economic growth, (e) anticipated energy consumption growth, (f) importation of electricity, and (g) existing nuclear capacity" [72].

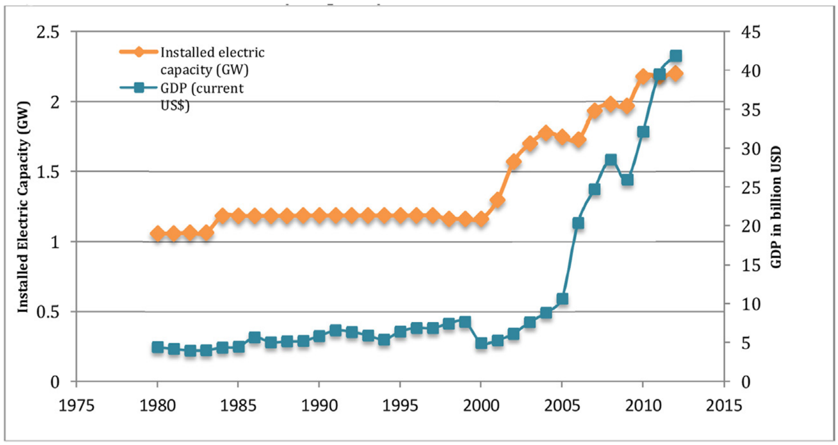

Fig. 1. Installed Electricity Capacity and GDP in Ghana.
Source: World Bank Development Indicators Database and Energy Information Administration, U.S. Department of Energy.

edly keen on the Rolls Royce 200-MWe SMR concept unveiled in 1978. The concept involved pre-licensed, standardized, prefabricated pressurized-water reactors (PWR) being mounted on barges and exported to developing countries. Rolls Royce's market study revealed wide interest in the reactor [75].[4] In 2011, the Deputy Director-General of the Ghana Atomic Energy Commission assessed the suitability of SMRs for Ghana's situation as promising because their construction would be "easier to finance" and appropriate to the size of Ghana's grid because in the event of a shutdown, the shortfall in electric power would be manageably low [76].

6. Constraints

Ghana has two primary techno-economic constraints on its nuclear choices. The first is that the installed capacity of electricity in Ghana is small when compared to a typical large nuclear power plant. As the graph below shows, the total installed capacity in the country has never been more than a factor of about 2.5 times the power produced by a typical large reactor, roughly 1 gigawatt (Fig. 1). The second is that Ghana's Gross Domestic Product (GDP) has historically been fairly low, and a large nuclear power plant costing anywhere from 5 to 15 billion dollars will prove quite expensive in relation to Ghana's GDP, which amounted to $39 billion in 2014 [77].

Ghana's current total installed capacity is 2831 MW [5]. Another 1230 MW of thermal, wind, and small hydro capacity is in the pipeline [78]. It is generally recommended that the size of a power plant unit should "not exceed 10% of the total electricity capacity in a country assuming it is all connected to a single grid. As a first approximation, the value of 10% of the grid capacity is a rule of thumb commonly accepted to be the upper limit for the capacity of any single additional unit of any type in order to prevent instability and unreliability of the grid system" [79]. Going by this rule of thumb, the maximum reactor size that would be recommended for Ghana is around 500 MW, even accounting for the plants under construction and others under consideration.

Large reactors from Russia clearly violate this recommendation. One could contrast this with the case of Ghana's flagship Akosombo dam. Although that plant is capable of generating 1020 MW, which seems large in comparison to the grid, the dam actually has six turbines, each with a capacity of 170 MW [80]. This allows the plant to operate with fewer turbines, either because of low water levels or because one or more turbines have to be shut down for maintenance.

One potential way to deal with the mismatch between the power capacity of proposed Russian reactors and Ghana's electricity grid is to connect the latter to the electricity grids of neighboring countries. This is not a new idea, and there is already a West African Power Pool (WAPP) involving 14 countries that have come together to establish a regional grid so as to be able to trade electricity. There are two problems, though. First, these grid interconnections are of very limited capacity in comparison with the power output of the reactors that are being planned. According to the World Bank, in 2012, the last year for which complete data is available, the combined installed capacity of the 14 countries that are part of WAPP was less than 12,000 MW. The capacity for electricity transfer is even smaller. Thus, even if all these countries were to expand their generation capacity significantly, it is unlikely to suffice for grid stability in the presence of two 1000 MW reactors in Ghana. Second, there are already ambitious plans to transfer electricity, including electricity generated with renewables [81], using those interconnections that have been built. Finally, within WAPP, Nigeria is planning to construct a nuclear plant in addition to Ghana [82], thereby setting the stage for potential conflict over which country's nuclear plant could export electricity.

The relatively small size of Ghana's GDP in comparison to the cost of a large reactor also imposes financial constraints. Historically, Pakistan is the only country to have successfully introduced nuclear power with a GDP of less than 50 billion US dollars [58]. This is one reason that Ghanaian officials see financing of nuclear reactor construction as a major challenge. As two senior energy policy makers put it, "Funding is one of the major challenges envisaged to face the Ghana nuclear programme. Being a developing country obtaining the necessary funds to run a nuclear power project, which is capital intensive, is not easy" [6]. Constructing a small or medium sized reactor can definitely help with this financing challenge because the initial investment required to build a single SMR will be considerably lower than that required to build a typical large reactor.

On the face of it, these economic and technical constraints on nuclear power plant development in Ghana are difficult to circumvent and it may not be easy for advocates of nuclear power, including the Ghana Atomic Energy Commission, to make a strong case for purchasing an expensive large reactor. This is likely one

[4] Besides Ghana, Rolls Royce also found interest in China, Australia, Isle of Man, the Canary and Channel Islands. No reactor of this design was ever built. This design is but one of the scores of reactor designs that were proposed but never constructed. Even now, there are numerous SMR designs on paper, but it is likely that the vast majority will never be constructed.

reason why despite the long history of planning to build nuclear power plants, Ghana has not yet acquired a nuclear power plant.

7. Institutional strategies

Ghana's choice of a reactor cannot be explained without considering the motivations of two institutional actors—GAEC and Russia's Rosatom. Both GAEC and Rosatom stand to gain should Ghana acquire a large reactor (VVER), and their separate interests feed on each other. GAEC is weak politically, especially in comparison to Volta River Authority, the traditionally dominant electricity producer, and has adopted a number of strategies to establish itself as a legitimate player in Ghana's electricity landscape. Rosatom's competitors are other vendors of nuclear reactors, both large and small. Although Rosatom has dominated the global reactor market since Fukushima, it has so far not obtained any contracts in Africa despite much effort, as described below; Ghana's acquisition of its reactor technology would allow it to establish itself as a reactor supplier on that continent.

7.1. GAEC

In terms of institutional power, the history recounted earlier offers evidence of GAEC's weakness in bureaucratic and institutional terms. As a 2008 U.S. diplomatic cable put it bluntly, "GAEC does not as an institution exercise final authority on the proposed nuclear energy policy" [110]. When it comes to the actual decision to purchase a nuclear reactor, it is probably the newly created Ministry of Power – formerly a part of the Ministry of Energy and Petroleum – that will exercise final authority. Another key player is the Energy Commission. The Energy Commission is broadly responsible for planning and assessing Ghana's potential energy opportunities within which nuclear power is one element. In addition, a number of organizations are also involved through the NEPIO including: the Volta River Authority (VRA), Ghana Grid Company, Ministry of Finance, Environmental Protection Agency, National Security Council and the Council for Scientific and Industrial Research (CSIR). GAEC officials will, of course, be involved in the decision but unlikely to shape it strongly.

Of these, the role of the Volta River Authority (VRA) may also be worth taking note of. VRA is a parastatal company that controls the bulk of electricity supply in Ghana and has historically been the institution that gained political power by offering the technological promise of cheap power for development, a strategy commonly adopted in many developing countries. VRA engineers and technical experts have traditionally been powerful players in energy policymaking in Ghana. Although their political power has declined somewhat in the decades since independence, what has supplanted them are independent power producers from the private sector, viewed as the solution to Ghana's electricity crisis in line with the neoliberal restructuring of the electricity sector undertaken in the last two decades.

In this milieu, nuclear advocates and GAEC seem to have adopted two other strategies to win support. One strategy has been to try and build alliances with other local bureaucratic players. GAEC's report put out on the occasion of its 50th anniversary (1963–2013) talks about how it "has metamorphosed into a formidable entity to support national development agenda" through "effective liaison with key stake holders" [83]. In creating liaisons with other institutions, GAEC prominently mentions how it participates in activities that would normally not be part of nuclear energy production, such as industry, healthcare delivery, security and agriculture [83]. It goes on to list various projects it has engaged in, including "the West African Gas Pipeline project and Bui Hydro Electric Power project" and "effectively monitoring the transport of goods in and out of our country". The very fact that such activities take the pride of the place in such a momentous report suggests that GAEC is forced to justify its present existence not through the generation of nuclear energy but by contributing to other activities that the state deems more valuable.

The other element in the strategy is aimed at garnering support from various international organizations and groupings for the Ghanaian nuclear program. One obvious source of international support is the International Atomic Energy Agency, whose statute calls for the agency to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world" [84].[5] GAEC has been a member of the IAEA since its inception and takes great pride in a Ghanaian being the first African appointed to chair the IAEA General Conference in 1962 [83]. In December 2014, officials from the Energy Ministry announced, with some fanfare, that the IAEA had given Ghana the go-ahead to develop a nuclear plant, which the Ministry of Energy projected as being operational by 2025 [86].

It is not clear what exactly the IAEA's go-ahead means. Under IAEA's Milestones approach for national nuclear infrastructure, the latest public commitments to a nuclear program demonstrate that Ghana has crossed the first of three Milestones. The more difficult task ahead is the creation of regulatory frameworks and institutions to guide preparatory work for construction, bidding processes, and plant commissioning [87]. Since that task has not yet been accomplished, invoking the authority of the IAEA is presumably meant to enhance the legitimacy of the nuclear establishment in Ghana.

More recently, Ghana joined the International Framework of Nuclear Energy Cooperation (IFNEC, formerly Global Nuclear Energy Partnership, GNEP) in 2007 [49]. IFNEC was set up in order to facilitate the process of new countries acquiring nuclear power, focusing on infrastructure development and other issues confronting newcomer states [88]. IFNEC, too, has been at the forefront of pushing nuclear power in Africa, co-hosting periodic conferences of government representatives. Further, one of the seven key areas IFNEC focuses on is small modular reactors [89].

As mentioned earlier, in July 2015, Ghana became a founding member of the African Network for Enhancing Nuclear Power Programme Development [2]. Many of the other countries that joined the group, including Egypt, Kenya, and Nigeria have historically held ambitions to establish nuclear power but, like Ghana, have so far not succeeded.

7.2. Rosatom

In recent years, especially in the aftermath of the Fukushima accidents, Russia has entered into various kinds of agreements with countries that currently have very few or no nuclear reactors. The Russian State Atomic Energy Corporation (Rosatom), according to its head, now has orders for 30 nuclear power plant units in 12 different countries – complete with signed contracts and firm guarantees – at a total value of over $300 billion [90]. While there is some doubt about the firmness of these guarantees and whether all these orders will come to fruition, it is clear that Russia is trying to secure as many orders as possible.

Africa has been a prime focus of Russian marketing as only one country, South Africa, owns an operational reactor. Russian interlocutors have been visiting many countries in the region and offering different arguments for nuclear power acquisition. In September 2015, for example, a senior official from Rosatom attended the annual Powering Africa conference held in Accra,

[5] The IAEA has been very active in promoting nuclear power in Africa in recent years [85].

Ghana and called for Sub-Saharan African countries to diversify their energy supplies and move away from fossil fuels [91].

It should not be surprising then that as signs emerged that Ghanaian policy makers were actively considering acquiring a nuclear reactor, Russia was quick to enter the scene. In 2012, Rosatom signed a nuclear cooperation agreement with Ghana for assistance in constructing nuclear power infrastructure [92]. This was followed by another framework agreement in June 2015 that "allows for development of the necessary contractual and legal framework for cooperation" and provides "the conditions for promotion of the Russian technologies" as well as "joint nuclear projects" [93]. This strategy of entering into a series of agreements is one that Rosatom has followed elsewhere. In the case of Egypt, which was initially undecided about whether or not to purchase a nuclear plant, "Rosatom [pushed]... for enough intergovernmental deals [for] a commercial contract...[to become]...ultimately inevitable" [94]. And, sure enough, in November 2015, the two countries signed an agreement for Russia to build a nuclear power plant in Egypt [95].

As mentioned earlier, the agreement with Ghana allows for the construction of a 1000–1200 MW Russian reactor. Thus far, public sources do not mention what design the reactor is to be. But, odds are that it would be of the VVER type, which comes in both 1000 and 1200 MW variants [96]. Although it has access to a number of other reactor designs, including small modular reactor designs [66,97–101], Russia has only entered into contracts to export VVER reactors in the last several years. This is the case with countries as varied as Turkey, Jordan, South Africa, and India [59,102–104]. This fact, in combination with the figures mentioned for the power output of the reactors planned for construction in Ghana, makes it seem quite likely that the reactor planned for construction is a VVER.

8. GAEC's attraction to big reactors

The institutional circumstances described above helps us better characterize the puzzle we started with. Despite its long years of existence, GAEC has been unable to get adequate political backing to see through the purchase a nuclear reactor. Given the current shortages of electricity in Ghana, GAEC is right now in a relatively favorable position to successfully advocate for the acquisition of a reactor. This could be either a small or a large reactor. On the one hand, there are technical and financial factors that would favor it choosing a small reactor. On the other hand, there is Rosatom that would naturally promote the choice of a large – Russian – reactor. Why have GAEC's leaders gone for the latter choice, even though it is difficult to justify on technical grounds?

Before coming to our answer to this question, let us first consider one argument offered by Ghanaian nuclear policy makers for why small reactors might be inappropriate to Ghana: the idea that the design should possess "technological maturity" [6]. A related idea is that the reactor chosen should be of "proven technology" that has been "in use for 10 years or with minimum modifications" of a proven design [76]. However, there is reason to think that this may be more of a rhetorical excuse rather than a critical consideration. While it is true that most of the new small reactor designs have not been constructed, Saudi Arabia has entered into agreements with South Korea and China to explore the construction of small reactors [105,106]. More important, China is in the process of constructing a small reactor that is expected to start operating in 2017 [107]. Further, in view of the fact that it would take more than a decade to construct a nuclear reactor in Ghana, GAEC could just as well have justified a small reactor through the argument that there would be operating small reactors in other countries by the time one started generating power in Ghana.

Our more substantial answer to this puzzle is that GAEC would like to capture the national imagination by offering a one-stop solution to Ghana's power problems: a nuclear equivalent of the Akosombo Hydroelectric plant, the country's most prestigious energy project ever. As the GAEC's National Nuclear Research Institute wishfully states, it has the "capability of managing nuclear power in the near future [and] finding a *lasting* solution to the energy crisis of Ghana" (our emphasis) [108]. Likewise, in 2014, the GAEC Director-General announced that "nuclear energy is *the viable option* to relieve Ghana from her present power crisis" (our emphasis) [109]. In 2010, the earlier GAEC Director-General told a U.S. State Department official that the government of Ghana had "no choice" but to acquire nuclear power plants, and that would enable the country to reach the "promised land of energy security" [110]. GAEC is also reported to have the "goal of someday achieving 40 percent of electricity supply from nuclear power, about double the current U.S. rate" [110]. GAEC evidently perceives the need to promise a lot if it has to get the go-ahead to construct any reactors at all.

The idea of a one-stop solution is why GAEC's preference for a reactor size has changed with variation in the unmet electricity demand. In 2007, when there was a shortfall of about 400 MW in the power supply, nuclear advocates recommended setting up a 400 MW reactor by 2018 [6].[6] Some years later, analysts from the World Bank were projecting that the power supply shortfall would keep increasing to reach 826 MW by 2022 [111]. In line with their earlier predilections, nuclear advocates started looking at building larger reactors, ranging from 700 to 1200 MW [112].

Likewise, a 2012 paper by analysts from the Department of Nuclear Engineering & Material Science, at the University of Ghana and GAEC officials estimated an energy shortfall of 1200 MW by the year 2020 [113]. The authors then went on to argue, "nuclear power could provide the energy deficit to the required capacity by 2020 and with almost unlimited technical possibilities for further expansion" [113]. The idea of expansion is becoming more common, with officials now talking about a second 1000 MW reactor after the commissioning of the first plant [114].

Such claims that GAEC will build one or more nuclear reactors by 2018 or 2020 (as projected earlier this decade) are, of course, speculative and almost certainly will not materialize within the promised date. But as Cynthia Selin observed, "speculative claims...are powerful constructions that create legitimacy in a technological domain" [115].

There may be a second incentive at work. Institutions like the GAEC have much to gain by proposing and executing large projects but relatively little to lose.[7] GAEC's two main rewards for being approved to construct a large reactor, as compared to a small reactor, are significantly greater political clout and a huge increase in financial resources. It is easy to imagine the difference between the situation where GAEC is responsible for 2000 MW of electrical generation capacity out of a total capacity of, say, 6000 MW and the situation where it is only responsible for 400 MW.

The bottom-line is that GAEC wants to portray itself as playing an important role in solving the national power crisis, and therefore a small reactor will simply not do. Indeed, when the Deputy Director General of GAEC was asked about the possibility of Ghana acquiring small reactors, he was explicit that building one or even two 300 MW SMRs will not suffice to meet the 735 MW gap between demand and supply experienced in 2014, and the prospects of receiving a governmental go-ahead for a nuclear plant would be

[6] To be precise, GAEC's assessment indicated that "a medium size pressurized water reactor (i.e. a PWR with capacity 300 MW–700 MW) is the most favorable type of reactor" [6].

[7] For a similar point in the context of Israel's capital market, see Ref. [116].

best if it involved a large reactor [117]. Evidently the financial and political cost involved in acquiring one or two SMRs is too high if their power output does not, even in theory, completely eliminate projected energy shortfalls.

GAEC's desire to promise a one-shot solution to the country's energy problems has been given a powerful boost by an external vendor promoting large reactors, i.e., Rosatom, which has been aggressively trying to enter the African electricity market. And, finally to complete the picture, there is the preference on the part of elected officials for large-scale projects [118,119]. Fifty years ago, hydroelectric power enjoyed this privilege across Africa. Now it is evidently the turn of (big) nuclear projects to play this role.

There is a parallel with the concept of entelechy that Kinsella identified as a characteristic of nuclear discourse. Kinsella argues that entelechy underlies the kind of logic that has led to the arms race: "If Hiroshima-scale fission weapons are understood as military assets, for example, then by implication thermonuclear weapons are better assets because of their greater potency, and large stockpiles of highly accurate thermonuclear weapons are better still" [31]. Likewise, for the GAEC, it may be argued, if small reactors are good solutions to the energy crisis in Ghana, then a large reactor must seem better. And two large reactors would be even better.

It is tempting to interpret this preference for large reactors as deriving from a socio-technical imaginary, to use the concept pioneered by Jasanoff and Kim [23,24], but this would be mistaken. For, as Jasanoff and Kim explain, sociotechnical imaginaries "are associated with active exercises of state power, such as the selection of development priorities, the allocation of funds, the investment in material infrastructures, and the acceptance or suppression of political dissent" [23]. This emphasis on the state suggests that the technological artifact that is more appropriately representative of the sociotechnical imaginary in the case of Ghana is the large hydroelectric dam, and GAEC's interest in a large reactor is an effort to evoke precisely the same imaginary that had so much power in the past to shape political and social pathways. As with the Akosombo dam, it remains for Ghana's government to prioritize nuclear power over other options for energy generation, allocate funds for construction and invest in the training of technical personnel.

GAEC's attempt has much in common with the archetypal "hero story" identified by Kathryn Janda and Marina Topouzi in their analysis of energy efficiency in buildings: within this "inspiring" storyline, "society is 'saved' by clever technologies" [14]. In GAEC's narrative too, "most of the heroic acts occur in the special world of the future" [14]. The future date is flexible but is chosen so as not to be too soon to make it seem completely implausible but not too far for fear of losing the interest of policy makers and the public. In 2012, for example, GAEC targeted 2020 as the date to achieve the heroic act – ending Ghana's energy shortages – through the use of their clever technology: the nuclear power plant [113]. By 2014, this date had shifted to 2025 [120].

GAEC's invocation of a one-stop solution to Ghana's energy problems would certainly have rhetorical utility in its efforts to construct a reactor. In addition to some of the problems that confronted GAEC in the past, nuclear energy is faced with a new challenge in recent years: the dramatic improvements in renewable energy technologies, a trend that has been used in arguments by those opposing nuclear power in Ghana [121,122]. GAEC's response to this has been to claim that Ghana's renewable energy resources are too limited to meet the shortfall of power and hope that "Ghana will get it right this time to solve its power problems by including nuclear in its energy mix" [76].

9. Conclusion

The history of over five decades of attempts to set up nuclear energy in Ghana, with nearly as many reversals as there have been proposals, is evidence that there is no consensus on acquiring nuclear power. A nuclear power plant cannot be set up in a matter of weeks or months, but requires political support for at least a decade and a half or two to go from conception to operation. Therefore, even periods of a few years of bipartisan support may not suffice for fruition. Nevertheless, in the last few years, there has been government backing and the country has taken some steps toward setting up a nuclear power plant. The question that we examine in this paper is what kind of reactor Ghana will procure.

One reason to ask this question is that there has been a widespread expectation that Ghana would be among the first African countries, other than South Africa, that would set up a nuclear power program. Because of Ghana's limited electrical and financial capacity, it has usually been assumed that its nuclear power program would involve small reactors, which have been held up as being more fitting to developing countries. In recent years, especially, several countries around the world have been pouring large amounts of money into the development of such reactors. And one argument that has been used to get government support for such investment is that there will be a significant market for these reactors in countries like Ghana with technical and economic constraints on their power plant choices. Thus, Ghana offers a good case study to examine if this expectation is being borne out.

When it comes to Ghana, this techno-economic argument does not seem to work. The Ghana Atomic Energy Commission is the main institution pushing for nuclear reactors, but its power to force through the purchase of a reactor is limited at best. In an attempt to get over this weakness, GAEC has attempted to position itself as a complete, one-stop solution to Ghana's electricity crisis, by calling for the construction of just one or two large nuclear power plants.[8] This is why GAEC's preferred reactor size has increased over the years with increasing estimates of electricity shortages in the country—resulting in the choice of nuclear plants that are inappropriate to Ghana's circumstances, both in terms of grid size and finance. GAEC's efforts have been upended in their influence by Russia, whose nuclear establishment is determined to dominate the reactor export market. In addition to offering to sell a large nuclear reactor with an electrical capacity that more than meets GAEC's desire to fill the demand-supply gap, Rosatom might even be able to provide financial assistance.

In this milieu, considerations such as grid stability and high costs of electricity generation are likely to be secondary. As far as we have been able to make out from the public record, there is no evidence that the question of grid appropriateness has been raised in the context of Russian reactors. GAEC itself would not have any motivation to examine this constraint, certainly not publicly.[9]

GAEC's apparent choice of a Russian VVER despite its failure to meet technical or financial constraints does have parallels in other countries. In the case of the Soviet Union, for example, Sonja Schmid has argued that the RBMK reactor design, the kind that exploded in April 1986 in Chernobyl, was "neither the cheapest nor the technologically most sophisticated design available, nor did it have the most substantial track record" [125]. Rather it was a range of other

[8] GAEC is by no means unique. Nuclear energy establishments in many countries have long hoped for receiving political backing for their pet nuclear power projects, but failed and have tried to stay alive by constantly making pronouncements about the need for nuclear power and the imminence of generating it. For a fascinating account of another organization in the same situation, Batan in Indonesia, and the strategies it has adopted to stay alive, see Ref. [123].

[9] In a different context, this deliberate cultivation of avoiding some questions has been termed the will to ignorance [124].

considerations, including the "organizational status of different research institutes", that helps one understand the Soviet decision to construct this reactor design. In India, despite the adoption of a much-heralded three-stage reactor program involving heavy water reactors and breeder reactors, the nuclear establishment imported VVERs from Russia for organizational and geo-political reasons [29].

Our analysis of nuclear reactor choice in Ghana has implications for the discourse about the energy transition in Africa. Having signed two agreements with Rosatom with progressively greater scope, Ghana is rapidly entering the phase in which it might be impossible to extricate itself from the purchase of a larger reactor, a feature that has been termed entrapment in a related context [126,127].[10] Should the sale be completed, the new power plant will add a tremendous burden to its grid (and grid managers), the Ghanaian electricity consumer and taxpayer. The huge costs involved in constructing and operating nuclear reactors will also imply that expenditures on other sources of power would be diminished, which would only prolong the electricity shortages that have been plaguing Ghana. Energy planners and policy makers in other African countries, such as Nigeria and Uganda that are also considering nuclear power, should pay particular attention to how the situation in Ghana evolves.

Although there is much discussion of small reactors being appropriate to developing countries, the case of Ghana suggests that the market for such reactors will likely be limited. A similar case study of Jordan found that the country was choosing a large Russian VVER in preference to a small reactor even though the latter might be more appropriate to Jordan's technical and financial circumstances [128]. This implies that in countries that are developing SMRs, government policies supporting the development and licensing of SMR designs should not be made on the basis of the presumption that there will be a large demand for such reactors in developing countries.

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Appendix.

GAEC has, on more than one occasion, argued that nuclear power was competitive with fossil fuels. In 2000, for example, GAEC estimated that nuclear reactors in Ghana would produce electricity at 4–5.9 US cents per kilowatt-hour (kWh), which compared well with a combined cycle thermal plant (5.0–5.5 cents/kWh) and hydro plants (6.9–8.1 cents/kWh); GAEC also argued that if "stringent environmental policies are put in place the cost of generating power from fossil fuels would increase significantly thus making nuclear power more cost competitive over fossil fuels" [129]. About a decade later, in 2009, GAEC estimated the cost of nuclear generation at 4.0–6.0 cents/kWh [130]. Given what is known about nuclear economics elsewhere, these estimates seem overly optimistic about the cost of nuclear power. What is also noteworthy is that GAEC's nuclear cost estimates did not change during the decade, whereas the same decade saw a significant increase in cost estimates of nuclear reactors around the world [131,132], another sign that GAEC was under-estimating nuclear costs. Therefore, we carry out a cost comparison between different sources of electricity generation for Ghana.

The conventional way to carry out an economic comparison between different sources of electricity is to calculate the levelized cost of electricity (LCOE). The LCOE is the ratio of two quantities. The first is the discounted sum of all the costs associated with generating electricity over the lifetime of the plant, including factors such as the capital cost of construction, the costs involved in operating and maintaining the plant, and the cost of loading fuel into the plant—for solar and wind energy, that is zero. For nuclear reactors, there is also the cost involved in dealing with the radioactive waste generated in the plant as well as dealing with various components of the plant that become radioactive over the course of operating the reactor. The second quantity is the discounted sum of electricity produced over the lifetime of the plant, which depends on the generation capacity of the plant as well as how efficiently it is expected to operate. Both of these quantities depend also on the discount rate, a measure of how future benefits are valued relative to current costs.

The contribution of each of these variables to the total cost of electricity production varies from one source of electricity to another. For example, for nuclear electricity, capital costs and the discount rate are the most important variables whereas for electricity produced by hydrocarbons, fuel costs are the dominant factor. Because of the dependence on financing parameters, the LCOE is also sensitive to the time period it takes to construct power plants. This is a particular problem for nuclear reactors, because they not only take long periods to construct, but many projects have experienced major construction delays that have resulted in huge cost overruns [133]. As a result, there is significant financial risk imposed by investment in nuclear power.

Even without delays, establishing a nuclear power program from scratch can take a considerable period of time. As an illustration of how long it may take for a country to construct its first nuclear power plant, one can consider the case of developing countries that have just one nuclear power plant (with 1 or 2 reactors). The average construction times – between the first pour of concrete and the plant being declared commercial – for their reactors are Brazil (19 years), Mexico (16 years), South Africa (8.5 years), and Iran (38 years) [134]. These figures do not include the lengthy preparation period before the actual commencement of construction.

This is a significant period of time that must be taken into consideration when comparing the economic competitiveness of nuclear power to renewables; solar projects typically have a 1–2 years construction period. If Ghana, for example, decides to build a nuclear reactor today, it will likely be 2030 before the reactor starts generating electricity. Therefore, any fair cost comparison must be based on what alternative sources of electricity generation might cost in 2030, or at least 2025, rather than today's costs. This is particularly relevant to renewable sources of energy, in particular, solar photovoltaic systems because their costs have been falling very rapidly [135–138].

Since Ghana has signed an agreement with Russia, as an illustration we use the experience of the two VVER reactors constructed by Russia in Koodankulam in India. Construction of these reactors started in 2002 and the first of these was declared operating commercially on 31 December 2014 [134]. The second reactor is yet to be completed, but is expected to come online in the next year or so. The distribution of expenditures is shown in Fig. 2.

The other assumptions are drawn from various places in the literature. The construction cost of the nuclear power plant is the most important component of the cost of generating nuclear energy. According to Rosatom, the Russian state company that sells nuclear reactors, its nuclear reactors cost around $3500–$4000/kW [139]. In light of the tendency for under-estimating of construction costs,

[10] William Walker argues that entrapment is an "unavoidable risk that attends the development of all complex systemic technologies, especially but not only where infrastructures contain large and lumpy blocks of capital. These technologies and their associated projects and policies cannot get off the ground unless organisations are prepared to make heavy commitments to them, and unless those organisations are tightly bound to their commitments through contracts and other devices" [127].

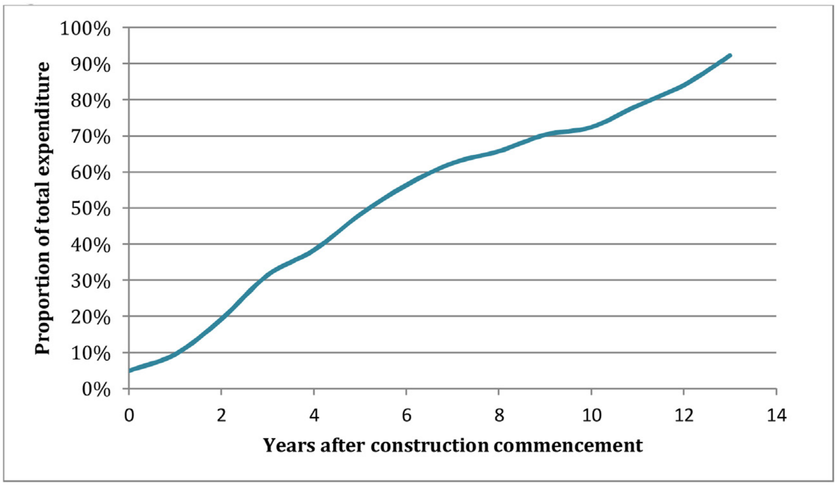

Fig. 2. Cumulative Distribution of Construction Costs.
Source: Reports from India's Ministry of Statistics and Programme Implementation. The X axis shows the year after construction commences, and the Y axis shows the fraction of total plant expenditure reached in that year.

we have chosen the upper end of that range as one case. In order to illustrate another plausible case, we have chosen $6000/kW as a notional construction cost based on estimates of $5530/kW by the U.S. Department of Energy's Energy Information Administration and of $7600/kW by the Wall Street firm, Lazard [140,141].

The operational and fueling costs for nuclear and conventional combined cycle gas plants are derived from the latest report on *Projected costs of generating electricity* by the OECD's Nuclear Energy Agency [142]. The cost of natural gas, the most important component of generating power at a combined cycle plant, is quite volatile and will depend on the source of the gas. Ghana's expected sources include the offshore Jubilee and Sankofa fields and the West African Gas Pipeline from Nigeria [36,143,144]. For the cost, we use $8.16/mmBTU, which is the weighted average of the gas cost from these different sources as estimated by the World Bank inflated to 2015 dollars [36]. The consumption of gas is set by the heat rate and we use the figure of 7772 BTU/kWh (8.2 MJ/MWh) that is assumed by the International Renewable Energy Agency in a 2013 study [81]. The combined cycle plant is assumed to cost $1000/kW, somewhat higher than the cost of $922/kW assumed for conventional combined cycle plants by the U.S. Department of Energy's Energy Information Administration, and much higher than the cost of $639/kW assumed for advanced combined cycle plants. Thus, our assumption for the capital cost of a natural gas plant will make nuclear seem more economically competitive than it might be in reality.

For solar photovoltaic projects, two representative capital costs are chosen. A value of $2000/kW is chosen on the basis of the finding by the International Renewable Energy Agency that "in Africa, the total installed costs for utility-scale [photovoltaic] projects in 2013 and 2014 spanned the range from USD 1 820 to USD 4880/kW" [145]; a low value is chosen in light of the fast declining costs of solar energy around the world. To take into account the fact that a nuclear plant, even if construction starts very soon, is likely to generate electricity only by 2025 or 2030, we also use the expected low cost of photovoltaic plant construction in that time frame. Specifically, we use the International Energy Agency's projection that "utility-scale capital expenditures cost would fall below USD 1/W by 2030 on average, but the cheapest systems would reach that mark by about 2020" [146]. This translates to a unit capital cost of $1000/kW.

Following other studies, we have chosen a real discount rate of 10% [81]. Our assumptions and results are summarized in Table 1.

These results show that it is very unlikely that nuclear power would be an economical means of electricity generation, either in comparison with natural gas or solar photovoltaic energy. Note that our generating cost estimate for solar energy is likely an overestimate. Already some utility scale photovoltaic projects around the world are generating electricity at $50/MWh or thereabouts [138,147,148]. This cost comparison does not include the significant upgrades in the grid – replacing equipment such as switchgears – required to ensure that the grid operates smoothly even during regular operations of the large reactor, let alone scrams.

Table 1
Comparative Cost of Electricity Generation.

	Nuclear		Combined Cycle Gas	Solar (PV)	
Unit Capital Cost ($/kW)	$6000	$4000	$1000	$2000	$1000
O&M cost ratio	2.50%	2.50%	4.50%	1.00%	1.00%
Fixed O&M ($/kW-y)	$150	$100	$45	$20	$10
Heat rate (BTU/kWh)			7772		
Gas used (mmBTU/MWh)			7.77		
Gas cost ($/mmBTU)			$8.16		
Fueling costs ($/MWh)	$10.09	$10.09	$63.41	0	0
Economic life	60	60	40	25	25
Capacity Factor	85%	85%	85%	20%	20%
Auxiliary Consumption	8%	8%	3%	0.25%	0.25%
Discount Rate	10%	10%	10%	10%	10%
Annualised Capital Cost	$1,312.60	$875.07	$107.69	$231.35	$115.68
Annual expenses ($/kW/year)	$225.10	$175.10	$517.17	$20.00	$10.00
Total generation cost ($/MWh)	$224	$153	$87	$144	$72

This result that nuclear power is much more expensive than solar power might seem counter-intuitive. The conventional wisdom about the high costs of renewable energy has been challenged in recent years because of the rapid decline in solar costs. These costs will decline further by the time any nuclear reactor can be built and hence the economic argument for solar energy as opposed to nuclear power will only become stronger with time [149–151]. These trends are the reason that in the United States, the electric utility Pacific Gas and Electric decided to shut down the Diablo Canyon nuclear power plant and replace it with a combination of renewable energy, energy efficiency, and storage technology [152].

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