Evaluating Electricity Generation Expansion Planning in Ghana

by

Sika Gadzanku

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Abstract

Ghana, a West African nation of 28 million people, provides an interesting case study on the interaction between power supply and politics in emerging economies. From 2012-2016, due to security of supply issues around hydro and fuel supplies, Ghana experienced the worst power crisis in its history with regular rolling blackouts. Rural and low-income urban areas and businesses were especially affected, and public discontent was palpable. The government's response was a reactive approach to generation expansion planning, focused on increasing supply. Power generation was opened up to the private sector and emergency power plants were procured. 93 percent of capacity installed during this post-crisis period was thermal generation, which increased dependence on natural gas and crude oil. Overall, this power crisis highlighted the cost of overlooking reliability and an undiversified generation mix.

I adapted a modeling framework to study Ghana's power generation system and I use a bottom-up capacity expansion and economic dispatch model to explore generation expansion pathways in the country under different settings, with the goal of providing insights into Ghana's capacity expansion decisions and identifying strategies that can help ensure better reliability and resiliency. Secondly, I use qualitative methods to evaluate Ghana's electricity infrastructure project financing framework to discuss how project financing shapes technology choices. I then explore potential policy and legal instruments that could support more robust systems planning in Ghana's electricity generation sector. Results reveal that a future power crisis is very likely given the high sensitivity of system reliability and resilience to natural gas and crude oil supply, global energy prices and transmission constraints. Strategies that could help avoid a future crisis include diversifying the generation mix, adding flexible generation (such as pumped hydro) to the mix, increasing transmission, and increasing the stability of fuel supply. This requires a holistic and coordinated approach to electricity planning between financial, technical, technological and political actors in the power generation sector.

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Chapter 1

Setting the Scene

1.1 Introduction

Ghana has experienced inadequate reliability and resilience in its power system throughout most of its history, especially in the last decade [5]. Resilience is the ability to anticipate, respond and adapt to disruptions to normal system operations while reliability refers to the ability to provide adequate and stable power to a system.

In 2014, the Ghanaian government announced two generation expansion goals - 5000 MW installed capacity by 2015 and 10% renewable energy (RE) by 2020. Yet, as of 2018, installed capacity stood at 3800 MW and renewable energy formed only 2% of the generation mix, and the government pushed back its goal of 10% RE to 2030 [23]. These goals were announced on the heel of rising electricity tariffs and the 2012-2016 power crisis, the worst in the country's history.

From 2015 to 2017, the average number of outages experienced by consumers in Ghana's metro areas increased from 18 to 48 per year despite the regulatory maximum of 6 power outages per customer per year [23]. During the peak of the crisis in 2014, consumers averaged 8 outages per month with each lasting at least 8 hours and back up diesel generators accounted for 12 percent of grid capacity [24]. These regular and often unannounced power outages, paired with rising electricity tariffs due to currency depreciation, outraged the public and led to the announcement of the ambitious aforementioned policy goals. Since energy planners had diagnosed the electricity issue as a problem of reliability, the policy goals focused largely on fixing power supply shortages through generation expansion.

These events in Ghana, an African country once seen as a beacon for successful electricity access planning, were the result of failing to prioritize reliability in electricity planning efforts. Since the Sustainable Development Goals (SDGs) were adopted by all United Nations Member States in 2015, academic and public discourse around SDG 7, which seeks to "ensure access to affordable, reliable, sustainable and modern energy for all" has centered on electricity access, often ignoring the poor rates of grid resilience and reliability [24, 25]. Sub-Saharan Africa (SSA) as a region has been of particular focus in universal energy access efforts because the region still has 600 million people without electricity access and its population is projected to double by 2050 [26, 27]. Yet as countries like Ghana and South Africa, which have relatively high electricity access rates (78 and 86 percent respectively) highlight, a focus on access without equally prioritizing reliability and resilience can have substantial economic and environmental drawbacks. Such losses include lost business productivity due to unexpected power outages, higher energy costs and increased air pollution due to using expensive back up diesel generation.

For my thesis, I adapted a modeling framework to study Ghana's power generation system and explore capacity expansion pathways under different settings, taking into account recent government planning decisions and future energy and environmental policies, and looking into associated system costs and the evolution of the country's energy mix. The main goal of my work is to provide insight into Ghana's capacity expansion decisions, and identify strategies that can help ensure better reliability and resiliency.

1.2 Motivation for the Study

This study is motivated by three key issues during Ghana's 2012-2016 power crisis: (1) the longstanding fuel supply concerns in the power generation sector, (2) the short-term focus of the government response during and after the power crisis, and (3) the financially precarious nature of power sector investments. Though low hydro inflows played a sizable role in the power crisis, fuel supply issues also severely constrained power generation. 60 percent of Ghana's power is generated by thermal power plants, making the stable supply of fossil fuels extremely important. Beginning in 2012, the primary source of gas supply for power generation at the time, which was Nigerian gas supplied through the West African Gas Pipeline (WAGP), became increasingly irregular and below contractually agreed terms, leading to increased dependence on more expensive crude oil and diesel.

Secondly, the initial government response and strategy thereafter became one of damage control and meeting short-term needs at the expense of long-term sector planning. Between October 2013 and March 2017, private investors installed 1731 MW of thermal power generation, representing 93 percent of all new installed capacity, which resulted in a shift from a hydro-dominant generation mix to a thermal-dominant generation mix. These investments reinforced the power sector's dependence on natural gas and oil, which was a core cause of the crisis.

Finally, financial challenges have plagued Ghana's power generation sector. Electricity is still heavily subsidized and despite the installation of pre-paid electric billing meters, significant leakage still occurs due to non-payment of bills by customers including major government agencies [5]. Additionally, during the crisis, ballooning fuel costs strained the state-owned Volta River Authority (VRA), then the sole power generator in Ghana, and by extension the government, which was struggling to cover large fuel costs. Furthermore, scandals erupted during the crisis with respect to the various contracts signed between the main electricity distributor, the Electricity Company of Ghana (ECG), and independent power producers (IPPs) [28–30]. In an interview with Ministry of Finance staff in November 2018, officials stressed the need for increased financial literacy training of ECG and VRA staff.

In September 2018, Ghana's president, Nana Akufo-Addo stated, "When we came into office, we inherited a plethora of IPP agreements, all of whom were contracted at the time of our crisis, and therefore, left us in a weak position, and got us accepting tariff rates of 18 cents per kilowatt hour (kWh) and over. In an era in the world where 10 cents per kWh is the maximum, we are producing IPP agreements at 18 cents per kilowatt hour. So, in future, we are going to insist that IPP arrangements are created out of competitive bidding, because it is only by that process that we will be able to get the competitive rates that both our domestic consumers as well as our industrial users need and can work with." [31]

To better understand how technical, political and financial factors shape power generation choices in Ghana, I use an integrated approach focused on a generation expansion model. Using this modeling approach, I explore long-term generation expansion planning pathways that can put Ghana in a better position to avoid future power crises.

1.3 Research Questions

This thesis aims to make methodological, practical and policy contributions to the body of research on Ghana's power sector and the wider academic discourse of Africa's energy future. First, I engaged with stakeholders such as independent regulators, bulk fuel suppliers, independent power producers and staff in the Ministry of Finance to gain clarity on the current state of the power sector. Then, I incorporated the feedback from the stakeholder engagement to inform our modeling approach. Finally, I assessed the range of policy instruments that could be of use in moving towards a more long-term electricity planning framework. **Figure 1-1** summarizes the research approach used in this work. The approach developed in this thesis can be replicated with relative ease to other countries looking to investigate the potential role of various generation technologies.

Practically, I grounded this quantitative assessment by exploring its connection with project financing mechanics. This analysis in turn informed subsequent policy analysis, which aims to contribute towards advancing robust electricity systems planning in Ghana on a national, sub-national and local scale. This work thus centers on the following questions:

- What has driven Ghana's power generation expansion strategy?

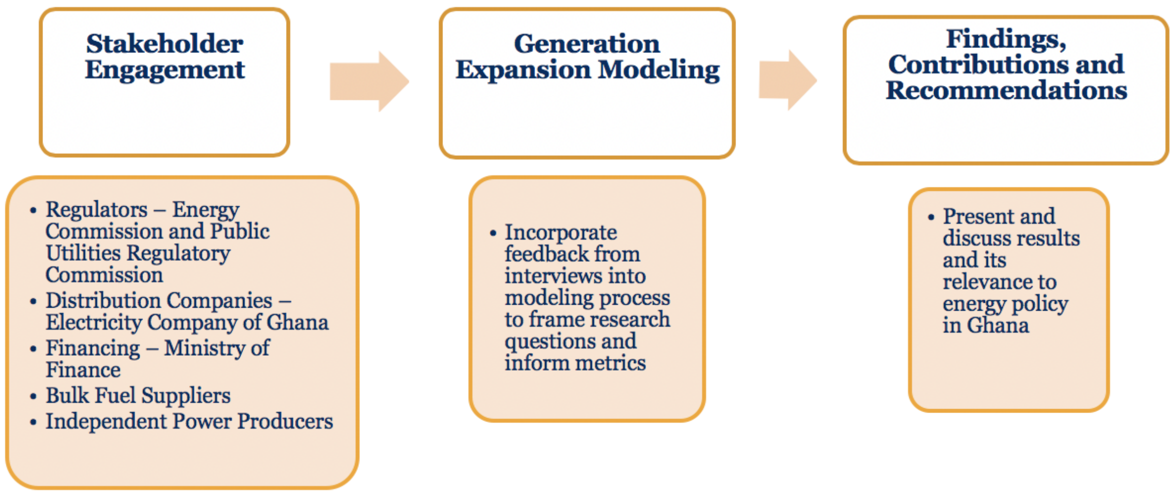


Figure 1-1: Research Approach

- How will Ghana's power generation investments increase long-term dependency on fossil fuels, and impact generation costs and CO2 emissions?
- How can Ghana strategize to avoid a future power generation crisis while keeping generation costs reasonable?

1.4 Structure of Thesis

This chapter has provided a brief introduction to my thesis research, described the main motivation for studying the problem, and the research questions I plan to address. The remainder of this thesis is divided into six sections. In Chapter 2, I provide a background on Ghana, diving into its social, political and cultural landscape, with a specific focus on the energy sector. Chapter 3 discusses electricity infrastructure finance in Sub-Saharan Africa (SSA) and the role of financiers in shaping generation investment decisions. Chapter 4 is a literature review of electricity planning and expansion strategies in Ghana, and the mathematical tools, such as SPLAT and SWITCH, employed in similar work. Chapter 5 covers the model methodology and formulation with an in-depth look at the data collection and processing process, choice of input parameters, validation of the model and, importantly, assumptions and limitations of the model. Chapter 6 presents the scenarios explored in the thesis and the key results obtained, and discusses their implications for electricity reliability and resilience. Finally, I conclude in Chapter 7 with policy implications of the study and recommendations for future work.

Chapter 2

Background and Context

2.1 Introduction

A prevailing hypothesis is that energy and industrialization are key to economic growth due to the strong correlation between energy sector development and high-income and industrialized nations. Consequently, there is a global push to support low-income, energy-poor countries develop their energy sectors. Some 600 million people in SSA still lack access to electricity and close to 3 billion worldwide have unreliable electricity access [26, 32]. Even though small-scale distributed energy is taking off in many developing countries, centralized grid electricity remains the dominant design of the electric grid [26]. To design the most economically efficient electricity system, as well as integrate environmental and social considerations into planning efforts, on- and off-grid electricity solutions require long-term planning across the generation, transmission and distribution arms of the power sector [33]. Each aspect of the power sector requires specialized data, analysis, decision making tools, and expertise to make optimal decisions. In this thesis, I focus on capacity expansion planning in Ghana and use various data sources, decision tools and policy analysis to explore the capacity expansion planning framework. To understand the current state of capacity expansion planning in Ghana, I begin with the history of power generation in the country. Then, I provide a background on Ghana's energy and electricity sectors and discuss how finance, integrated resource planning, and reliability and resilience standards contribute towards efforts to provide reliable, affordable and clean energy.

2.2 Post-independence politics and electricity in Ghana

Prior to independence in 1957, Ghana, which is located on the West African coast and sandwiched between the three Francophone countries of Burkina Faso, Cote d'Ivoire and Togo, was known as the Gold Coast due to its vast gold, timber and cocoa resources. The Gold Coast was colonized by the British Empire from 1867 to 1957. The British gradually conquered all the indigenous empires and imposed their British-style education and centralized government leadership style. By the 1940s, the indigenous population, who had been educated by the British colonizers and European missionaries, soon formed a nationalist and pro-independence movement. Led by Dr. Kwame Nkrumah, the charismatic, socialist and pan-African leader of the Convention People's Party (CPP), Ghana finally attained independence from the British in 1957 [34].

Upon taking reins of the country in 1957, Nkrumah soon grappled with balancing political and economic interests, especially in pursuing energy independence. The backbone of his state-led development agenda was to develop a hydroelectric dam on the Volta River in Eastern Ghana, known as the Volta River Project (VRP)[35]. It required a significant financial investment that the newly independent state lacked and so Nkrumah went on a charm offensive to secure the necessary funds. This fundraising campaign coincided with an interesting geopolitical period between Eastern and Western power blocs that left newly independent African nations squarely in the middle. From 1957 to 1960, 32 states in SSA attained independence. They were immediately courted by the Eastern power bloc yet overlooked by the West, especially the United States. The U.S. was then led by President Dwight Eisenhower who did little to hide his disregard for Africans. Many African nations were thus decidedly anti-American and adopted a pro-Soviet Union politic [35]. These African nations, and many others around the globe soon formed the Non-Aligned Movement (NAM) in 1961, which was committed to the "struggle against imperialism, colonialism, neocolonialism, racism and all forms of foreign aggression, occupation, domination, interference or hegemony as well as against great power and bloc politics" [36].

As one of the leaders of NAM, Nkrumah was aware of his political currency and used this to his advantage in his VRP fundraising campaign [35]. He soon adopted a more reconciliatory approach towards the U.S. and its new, more pro-Africa leader, President John F. Kennedy. Kennedy, who largely agreed with the anti-imperialist and pan-African goals of NAM, jumped at the opportunity to build political capital with Nkrumah. His government provided $40 million dollars ($334 million in 2017 dollars) in financial support [35]. Once the VRP was commissioned in 1966, it became the largest man-made lake in the world, powering the Akosombo hydroelectric dam, Ghana's single largest power generation source [35]. Even though Nkrumah would be overthrown later that year in a coup d'état, his long-term vision for a prosperous and energy independent nation laid the groundwork for Ghana's electricity sector.

2.3 The Hydropower Boom in Ghana and beyond

Sub-Saharan Africa is in the midst of a boom of hydropower projects because the region has vast hydro resources and hydropower is a well-established technology that remains relatively inexpensive and can help improve electricity access [16]. A review of hydropower development in the region suggests a recent resurgence in dam projects due to increased financial and technical assistance from China [37–39]. China's "going out" policy seeks to transfer some labor-intensive industries to elsewhere in the world, and to hedge against slowing domestic demand for large infrastructure projects [40]. Africa and Southeast Asia have since become China's largest market for hydropower. Since 2005, it has been responsible for at least 60% of Africa's hydropower projects [41]. In Ghana's case, another hydro plant, the Kpong Dam, was built in 1982 and hydroelectricity remained the sole source of power until 1998. Its third dam, Bui, was completed in 2013 and was financed and built by Sinohydro, the Chinese state-owned enterprise (SOE) under a Build, Operate, Transfer (BOT) construction agreement [16, 37, 38]. Though this dam boom reduced the energy gap in Ghana and other SSA countries, some soon experienced power crises due to variability in rainfall that exposed an over-dependence on hydropower [17].

In Ghana's case, three out of its four power crises were due to droughts that required curtailing hydro production. Studies suggest an increasing number of power systems are increasingly vulnerable due to this dam boom and possible future changes in rainfall patterns. In Eastern and Southern Africa, assuming completion of planned dam projects, hydropower dependency (the proportion of the generation mix sourced from hydropower) will increase from 62% to 82% in the Nile basin and 73% to 85% in the Zambezi basin [17]. The degree and sign of future rainfall in Western and Central Africa however remains unclear. The concern is that a reduction in rainfall would threaten the financial viability of many of these large hydropower projects and threaten system reliability and resilience. On the other hand, failing to capture increases in rainfall would lead to foregone revenue [16]. **Figure 2-1** gives an overview of the level of power generation across SSA and the current state of scholarship on the hydro-dependency of the region's power sectors. The four charts in the figure, representing the region's four power pools provide comparisons of 1) electricity access, hydro-dependency and projected population growth and 2) the level of research in each region for different methods of analysis (optimization and/or economic analysis, climate modeling, power pool analysis, country or basin-specific analysis, high-level commentaries, and policy analysis). We see that while all regions expect high population growth, they have varying degrees of electricity access, hydro-dependency and research coverage. As a whole, the West African Power Pool (WAPP) has the highest electricity access as well as high hydro-dependency. Within WAPP, Ghana has among the highest access (78%) and its current hydro-dependency rate is 40%, down from 78% in 2015 [42].

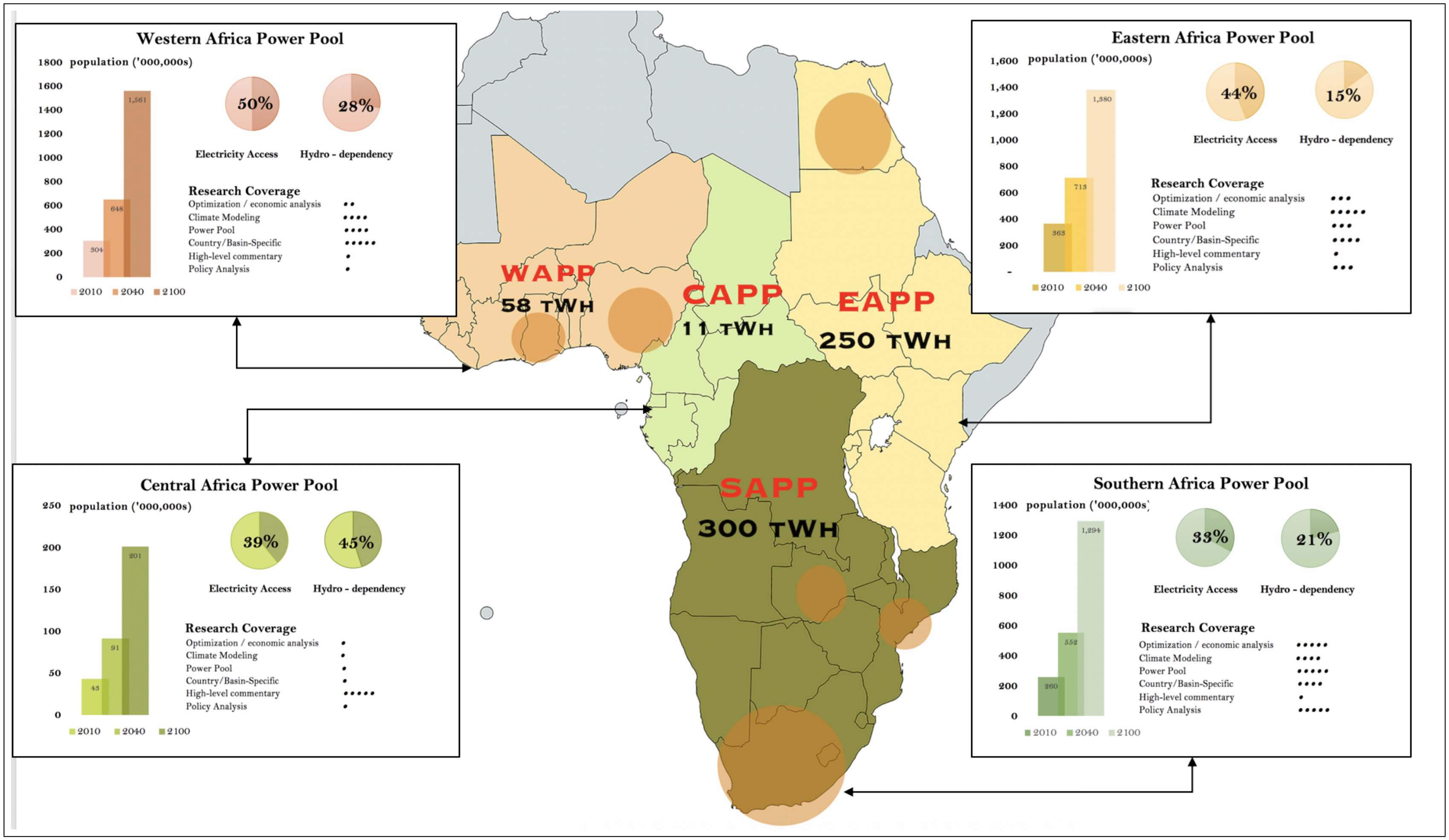


Figure 2-1: State of electricity access and hydro-dependency in sub-Saharan Africa

2.4 Energy and Electricity in Ghana

2.4.1 Ghana's Petroleum and Natural Gas Industry

Ghana's energy sector includes the power, petroleum and natural gas, and biomass sectors. The country generates most of its electricity from hydro and thermal power (mainly oil and natural gas). Since 2015, the domestic petroleum sector has provided most of the natural gas used in power generation, replacing Nigerian gas imported through the West African Gas Pipeline (WAGP) as the dominant source (see **Table 2.3**). Prior to commercial petroleum reserves being discovered off Ghana's shores in 2007, the country had some small-scale production in the Tano and Keta Basins. This all changed in 2007 with the discovery of the Jubilee field, thought to hold an estimated 700 million barrels of oil and 800 billion cubic feet of gas [43]. The TEN (Twenneboa, Enyenra, and Ntomme) and Sankofa (Sankofa, Gye, and Nyame) fields were also discovered soon after. TEN has an estimated 240 million barrels of oil and 396 billion cubic feet of gas, and Sankofa has an estimated 500 million barrels of oil and 1.45 trillion cubic feet of gas [43]. **Table 2.1** summarizes total crude oil production across these three fields from 2008-2017 and **Table 2.2** shows total crude oil imports for refinery and electricity generation use.

2.5 Power Generation in Ghana: Overview of Generation

Despite bold goals of 5000 MW of generating capacity by 2015, Ghana's dependable generation, which is slightly lower than the total installed capacity, stood at 2,533 MW in 2015. Even though power generation remained state-owned and controlled

Table 2.1: Crude Oil Production in Barrels (NE: Not in Existence) [18]

Year	Jubilee Field	TEN field	Sankofa Gye Nyame Field
2008	NE	NE	NE
2009	NE	NE	NE
2010	1,267,700	NE	NE
2011	23,757,695	NE	NE
2012	28,831,136	NE	NE
2013	36,760,348	NE	NE
2014	37,201,691	NE	NE
2015	37,411,661	NE	NE
2016	23,981,640	5,316,140	NE
2017	32,749,975	20,452,577	5,455,512

Table 2.2: Crude Oil Imports in kilotonnes [18]

Year	Total Import	For refinery	For electricity generation
2008	1976	1397	579
2009	983	441	541
2010	1662	961	701
2011	1532	1274	257
2012	1210	506	704
2013	1302	374	928
2014	693	70	623
2015	311	62	249
2016	1446	989	457
2017	233	55	178

Table 2.3: Annual Gas Supply for Power Generation (in '000s of MMBTU) [18]

Year	WAGP (Nigeria)	Ghana Gas
2009	198	
2010	15,617	
2011	30,525	
2012	15,447	
2013	11,573	
2014	22,541	2,040
2015	20,625	26,391
2016	4,003	23,473
2017	11,713	33,749

until 2013, all energy infrastructure projects had been partly funded by foreign actors. As mentioned previously, the Akosombo Dam and Takoradi Thermal Plant were funded by Western donors and the Bui hydroelectric power plant was developed by Chinese firms. These three power plants account for 46 percent of Ghana's generating capacity, highlighting the critical role these actors played in expanding Ghana's electricity generation fleet. **Figure 2-2** shows yearly capacity additions by type. Almost all power plants currently under development are thermal generation. This heavy dependence on thermal and hydro generation makes the power sector vulnerable to global energy prices, fuel supply problems and rainfall variability [5]. In 2018, 39% of generation came from hydro and 61% from thermal, of which 18% was oil, 4.4% was liquified petroleum gas and 78% was natural gas [44].

2.5.1 Power Crises

From 2012 to the end of 2016, Ghana went through the fourth major and worst power crisis in its history. Rolling black outs were the norm and at its peak, residents had 12 hours of electricity every other day. These black outs were due to several reasons

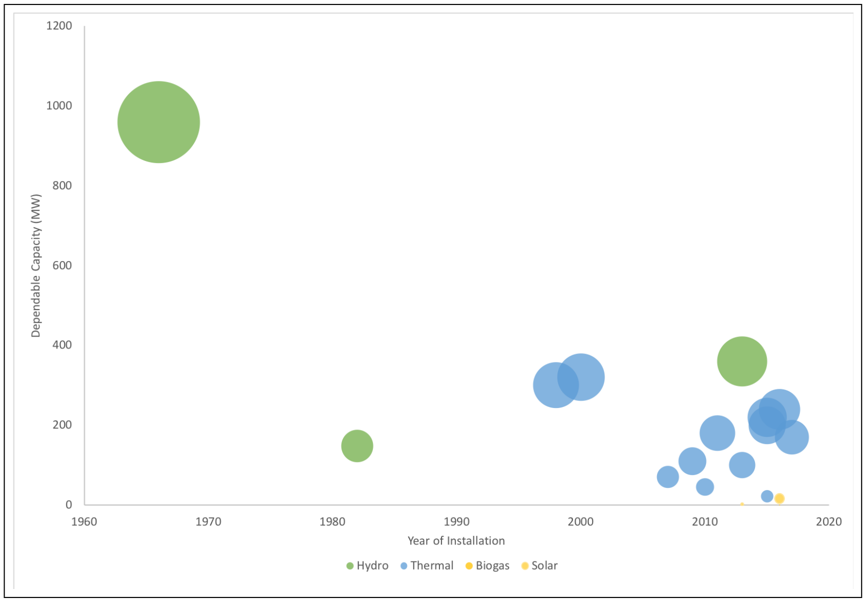


Figure 2-2: Yearly capacity additions by technology and fuel type (1966 - 2018)

including low water levels in hydroelectric dams, increased fuel costs, fuel supply shortages, and the lack of a cost-reflective tariff structure. **Figure 2-3** shows the timeline of the four power crises that have occurred in Ghana since the 1980s. In the case of the most recent crises, first, gas shortages due to a damaged West African Gas Pipeline (WAGP) severely impacted power generation and required power plants use expensive crude oil for generation, which significantly increased operating costs. Since the state-owned Volta River Authority (VRA) was the only utility in operation at that point, the government had to provide the extra funds to purchase fuel. They could not keep up with fuel payments so gas suppliers also held back some supply [1, 5]. Secondly, hydropower generation had to be reduced because Akosombo had a couple of low hydro inflow years. Finally, the power crisis was exacerbated by currency depreciation, which increased operating costs and required increases in tariffs leading to intense public blowback. The bottom right of **Figure 2-3** shows

Figure 2-3: History of power crises from 1998 - 2016 [1]

the electricity demand gap from 2010 to 2016 and end-user electricity tariffs in both Ghana Cedi per kilowatt-hour (kWh) and United States dollars per kWh. As shown in the figure, existing generation could only meet roughly fifty percent of demand, necessitating rolling black outs. Concurrently, Ghana's currency was depreciating so consumers were experiencing regular power outages while tariffs increased by over 400 percent in a five-year span. Given these shocks to Ghana's electricity sector, intense debate resumed on measures to further reform the sector.

In response, attention was turned to the country's two distribution companies in charge of fee collection and installation of pre-paid meters, the Electricity Company of Ghana (ECG) and the Northern Electricity Distribution Company (NEDCo.). At that time, both averaged revenue collection losses of 24 percent. Additionally, two emergency thermal plants, Karpower Barge and Ameri, were procured to help close the supply deficit and power generation was officially opened up to the private sector.

Table 2.4: 2013 Gazetted Feed-in-Tariffs in Ghana [2]

Renewable Energy Technology	FIT effective September 2013 (GHS/kWh)	FIT effective September 2013 (US Cent/kWh)
Wind	32.11	15.15
Solar	40.21	18.97
Hydro (< 10 MW)	26.56	12.53
Hydro (10-100 MW)	22.74	10.73
Landfill Gas	31.47	14.84
Sewage Gas	31.47	14.84
Biomass	31.47	14.84

Yet, efforts really focused on plugging the revenue loopholes in the distribution arm of the value chain [45, 46].

2.5.2 Alternative Power Generation Sources

In the wake of the power crisis of 2007 and 2008, Ghana announced plans to develop its renewable energy sector. A 2010 national energy policy set a target of using renewable energy to meet 10% of Ghana's energy needs by 2020. This plan largely focused on grid-connected renewables such as utility solar PV, onshore wind, waste-to-energy and biomass. Ghana's intent to grow the renewable energy industry was codified by the 2011 Renewable Energy Law, which has provisions for the feed-in-tariffs shown in **Table 2.4**, renewable energy purchase obligations (RPO), net metering for distributed generation and off-grid and mini-grid electrification for isolated communities [20]. Despite these policies, the country's utility-scale renewable energy industry has struggled to take off. As of 2018, Ghana had only three utility PV plants with a combined capacity of 42.5 MW, one biomass power plant and no other non-hydro utility scale renewables [42]. The slower-than-expected growth in grid-scale renewables led to an amendment in 2018 to push the deadline for 10%

renewables goal from 2020 to 2030. Wind and solar projects are expected to come online in the next few years.

As a member of the Economic Community of West African States (ECOWAS), Ghana also supports regional efforts to integrate renewables into the grid and improve overall system reliability and resilience energy planning. It is an active member of the ECOWAS Centre for Renewable Energy and Energy Efficiency (ECREEE) and the West African Power Pool (WAPP). WAPP coordinates cooperation between electric utilities across the region towards the full integration of the generation and transmission of electricity. ECREEE is tasked with implementing the strategic goals of ECOWAS to support sustainable development in an economically, socially and environmentally responsible manner [13].

Beyond solar and wind, the Government of Ghana highlighted waste-to-energy (WtE) technologies as an alternative generation source in the 2010 Strategic National Energy Plan (SNEP) with WtE projected to contribute 140 MW of generation capacity by 2020 [12]. WtE transforms waste into useful forms of energy such as electricity and heat. Current WtE processes include gasification, incineration and pyrolysis of waste such as municipal solid waste (MSW). In Ghana, WtE was envisioned as both an energy source and a waste management option [12]. As highlighted in "Future directions of municipal solid waste management in Africa", many strategies are being undertaken to better dispose of MSW [47]. In Accra, Ghana's capital, a waste management crisis has emerged as local authorities are unable to adequately manage waste. Oteng-Ababio (2013) reported that in 2010, the Accra Metropolitan Assembly (AMA), in a bid to overhaul its waste management system by improving collection and maintaining dump sites, spent 91% of its annual budget on waste collection [48]. Yet, these efforts proved unsuccessful and the waste management crisis led to a cholera outbreak between December 2010 and March 2011 [48]. Even though Ghana's 2010 Energy Policy document stated an intent to develop a WtE industry, a review of subsequent policy and the current state of businesses in the space reveal a relatively non-existent sector. First, the scale of the issue requires planning across all parts of the waste management value chain, which was missing from the start [47]. Secondly, an interview with an entrepreneur who used to operate in Ghana's WtE space revealed a frustratingly bureaucratic system with significant barriers to obtaining the necessary permits and the recurring issue of demands of bribes from the policymakers overseeing this issue.

2.5.3 Electricity Regulation

Figure 2-4 shows the institutional structure of Ghana's electricity sector. Ghana's electricity sector is under the jurisdiction of the Ministry of Energy and regulated by two quasi-independent regulators, the Public Utilities Regulatory Commission (PURC) and the Energy Commission (EC). PURC and EC were created under the 1997 PURC Act and the 1997 EC Act to attract private sector investment. The PURC act defined the roles of both entities - PURC monitors and set rates, oversees the electricity market and spearheads consumer protection and the EC sets standards and advises the Ministry of Energy on energy policy [49, 50]. Both bodies are positioned as independent regulators. Points of note in the act include:

- Section 3 of the EC Act of 1997, states, "The Minister may, in the public interest, give to the Commission directions of a general character relating to the performance of the functions of the Commission [50]", suggesting the ministry and the regulators are not wholly independent. Within this discussion is the assumption that the PURC and EC operate independently. However, evidence

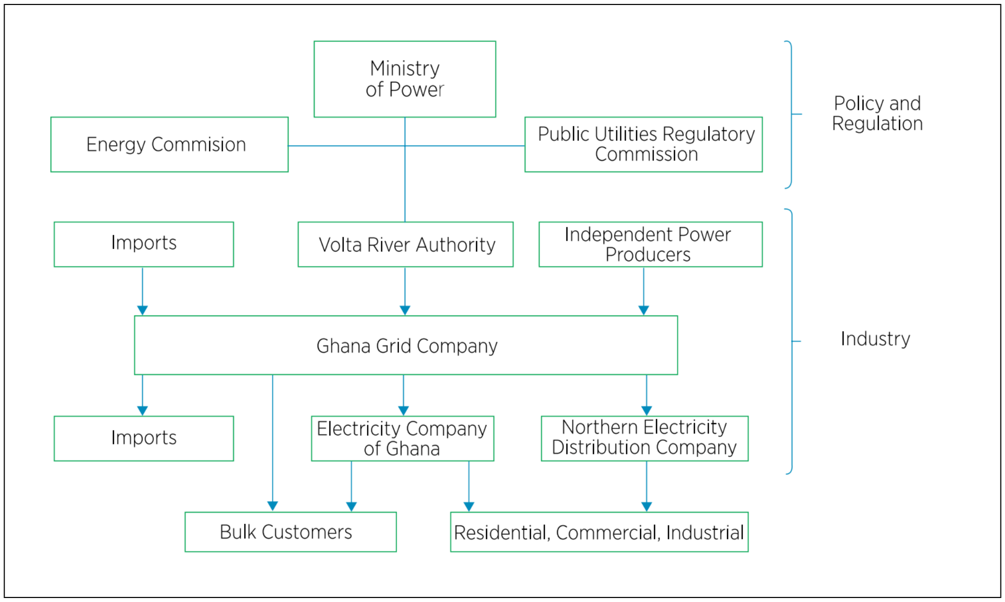


Figure 2-4: Ghana Electricity Sector Institutional Structure [2]

suggests political influence and bias can occur. The President appoints the commissioners and board members of both bodies. Since electricity prices are a hotbed political issue, tariff increases have been frozen or even reduced in the past in response to public outcry. This type of regulation by the PURC and EC can severely constrain the financial and operational efficiency of the power generation sector.

- Section 20 states that electricity rates must be uniform around the country, which raises issues around the tariff structure since distribution and transmission costs vary with location of the power plants and end-users. Rate setting has become a central issue in discussions of sector reform because it is strongly tied to cost recovery. In setting tariffs, the PURC Act requires consideration of 1) consumer interest 2) investor interest 3) assurance of reasonable production costs 4) assurance of financial viability of public utility 5) national economic growth 6) best use of natural resources 7) uniformity of prices throughout the country and 8) competition among utility companies. Depending on the metric used, some of these criteria are in direct tension such as 1) and 2), and 3) and 4).

- Section 27 is very specific with performance standards for the sector - voltage stability, maximum number of scheduled and unscheduled outages, number and duration of load shedding periods, and metering.

- Section 30 exempts the VRA from the supply and generation licensing requirement. This suggests that the VRA might be able to bypass the independent regulator when developing new generating facilities. It gives the VRA an edge in the project development process compared to independent power producers (IPPs).

- Section 34 grants the PURC authority to engage experts and consultants as it considers necessary.

2.5.4 Electricity Tariffs and Rate Design

As highlighted in the previous sections, tariffs are central to utilities' cost recovery levels. Good tariff design determines how and by whom electricity services are paid for in a fair and appropriate manner. Costs recouped through tariffs include those associated with energy, distribution network, capacity and ancillary services, transmission network, general and administrative services, taxes and policy, and system operation costs. The proportion of these costs vary significantly from country to country.

Figure 2-5 shows a range of pricing options that can be used in cost recovery. Economic and electric sector experts are increasingly making the case for dynamic pricing that reflects the value of energy at any given time and location. They contend that such pricing is the economically efficient and allow consumers and producers to obtain the best outcome [51]. However, dynamic pricing is difficult to implement because electricity is considered a public good and often used to achieve various economic and social goals. For example, rate design often aims to achieve allocative equity, social justice (where tariffs are designed to provide positive distributional outcomes for low-income, fixed-income and rural consumers), gradualism (since sharp tariff increases are very unpopular), and understandability (where tariffs are easily understood by consumers). These goals are succinctly summed up by the 10 Bonbright Principles of effectiveness, revenue stability or predictability, stability and predictability of the rates themselves, static efficiency, cost-reflectiveness, fairness, avoidance of undue discrimination, dynamic efficiency, simplicity in payment, collection, and freedom from controversies [3]. The degree to which each is applied, enforced and prioritized can create concerns around affordability and transparency [51].

The lack of cost-reflective tariffs in most of SSA is a large contributor to the inefficient operation of utilities. However, in many of these countries, increasing tariffs is tantamount to political suicide. So, electricity tariffs remain low and remain central to debates around the best strategies to improve access and reliability. This, on top of the technical (transmission and distribution) and non-technical (billing and fee collection) losses, have resulted in all but two African utilities consistently recording heavy losses [11]. Ghana has a tiered electricity tariff structure, based on the end user type with tariffs for bulk generation, transmission, and distribution service charges. End-users are broadly split into residential and non-residential customers. Within

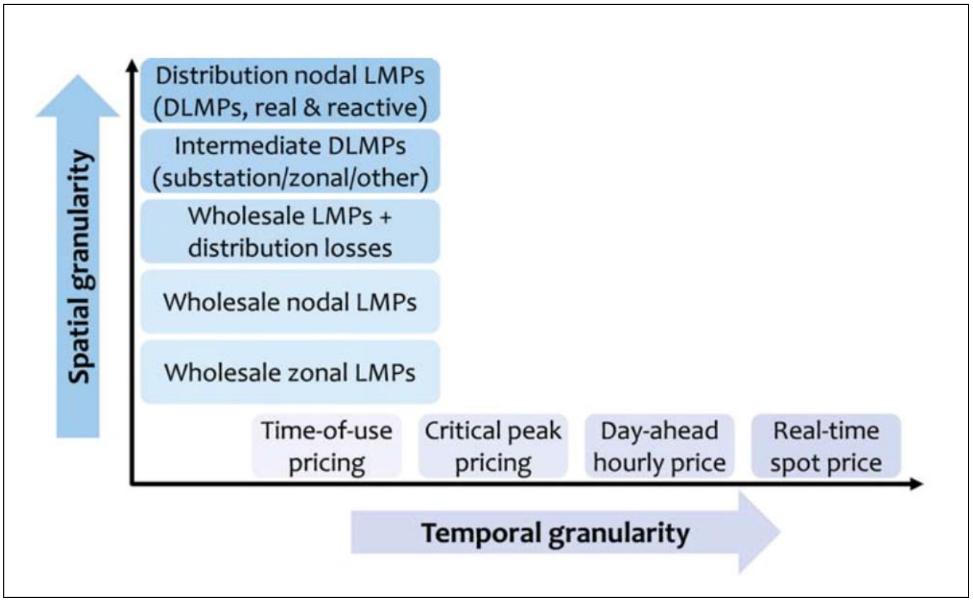


Figure 2-5: Choices in Adoption of Temporal and Spatial Granularity in Energy Pricing MIT Utility of Future Study [3]

the residential customers, PURC sets a lifeline tariff, which applies to all residential users. Lifeline tariff calculations are informed by prevailing economic factors including the national monthly minimum wage, ability of rural customers to pay, kerosene prices (kerosene is widely used as a cooking fuel), and average costs of hydroelectric power, which forms baseload electricity generation supply. Since this lifeline supply safety is not targeted to only those that need it, some revenue is lost. There are also non-residential users, from which the bulk of revenue is generated that are categorized into SLT-LV (low-voltage), SLT-MV (mid-voltage), and SLT-HV (high-voltage) users [50]. Ghana's tariffs across different customer classes are shown in **Figure 2-6**. Still, Ghana has a relatively flat tariff system. Arguments for this type of tariff, or more accurately, against dynamic pricing usually revolve around the cost of advanced metering infrastructure on residents and utilities, the possible inelasticity of demand and inability of consumers to be informed by information on their usage, and the

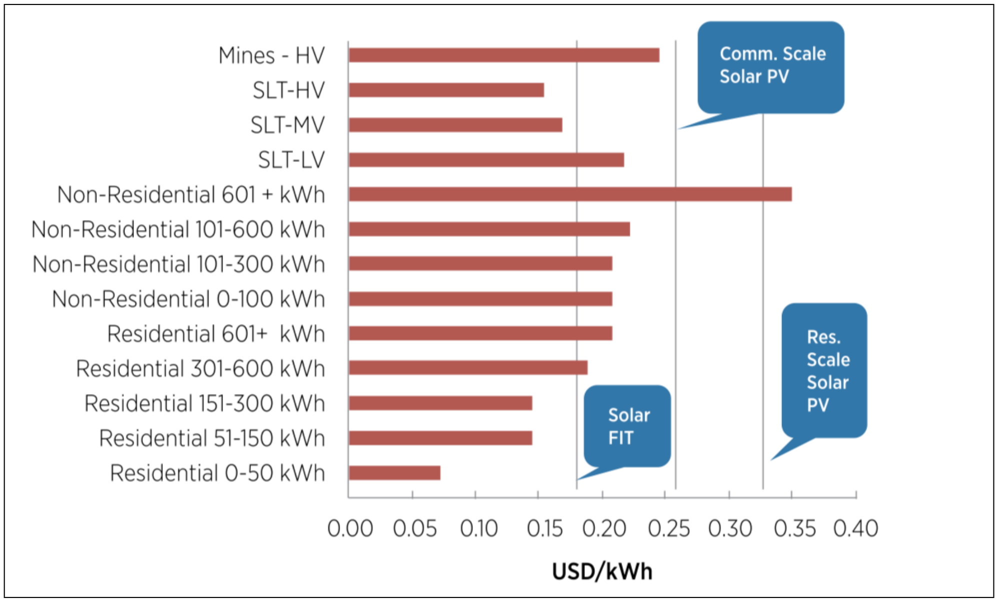


Figure 2-6: 2013 Tariffs Across Consumer Classes Compared to Feed-In-Tariffs [2]

redistribution effects of dynamic pricing [51].

Very little peer-reviewed research has been conducted to test which electricity tariffs would be appropriate for Ghana. Edjekumhene et al (2001) conducted a study that concluded that proper tariff adjustment was the biggest obstacle facing power sector reform in Ghana because of the question of how to adjust tariffs to economic levels yet keep them affordable and accessible enough to low-income urban and rural customers [49, 52, 53].

2.5.5 Electricity Access, Reliability and Development

Efforts to achieve universal electricity access in SSA in recent years have been especially unique due to advances in distributed energy resources (DERs), financing for energy access, and the scale of the electrification problem. Historically, energy access was extended to rural and sparsely populated regions through government subsidized rural electrification efforts, which usually involved extending the grid to these customers. Grid extension to rural areas requires significant upfront costs by utilities and distribution companies (who need to build out networks) and by the customers (who usually need to pay a high upfront fee to be connected to the distribution network) [11, 52, 53]. This cost was historically subsidized by foreign governments, including the United States, Indonesia, and China [32, 54–57]. Due to the growth of DERs, efforts are focusing on leapfrogging the traditional grid design to invest in off-grid and mini-grid solutions that are still expensive, but do not require the high upfront transmission network costs. Even though mini-grid and off-grid solutions can be cheaper than grid extension, off-grid solutions like solar home systems (SHS) may only provide a temporary solution to the problem. SHS can only provide energy to charge a few electronic items, but do not currently have the bandwidth to support increased energy consumption by rural customers [52]. Mini-grid solutions on the other hand can provide the necessary scale to meet robust energy needs of a rural community [52]. Furthermore, last mile connections, which refer to the distribution networks that connect consumers to sub-stations, are also very expensive and usually increase with distance of the consumer from the closest substations [52, 53]. Thus, in sparsely populated regions with consumers spread all over, the connection costs for these last-mile connections, especially if the consumption of users remains low, can be a barrier. In countries with underdeveloped grids, most of these far out consumers are usually rural low-income populations, whose willingness to pay for such connections would be very low [52].

2.6 Reliability Standards

Reliability can be defined as "the probability of a device or system performing adequately, for the period of time and under the operating conditions intended [4]" Reliability in the power sector is the ability to meet energy needs through generation adequacy, while reliability standards are the requirements mandated or recommended for the efficient operation and planning of the electric power system [58]. In most jurisdictions, these standards are set to reflect the technological, economic, and technical capabilities of the system. Typical reliability indices measure load interruption, loss of load probability and outage frequency and duration, which cover the range of performance standards expected for the successful operation of the power generation aspect of electricity planning [4]. Generating unit operation constraints strongly influence how the system should be designed to meet reliability standards. **Figure 2-7** shows the different operational states of a generating unit, which impact their availability and contribution to system reliability. As seen in **Table 2.5**, there can be a large difference between projected and actual availability, which can threaten system reliability. In most power systems, meeting these reliability standards are now largely achieved through ancillary services.

2.6.1 Ghana's Reliability Standards Story

Reliability in Ghana's power system is mainly measured using three reliability indices and two main reliability standards, which are defined over three types of operational areas (metro, urban and rural), and for which Ghana has set targets via regulation [18]:

- System Average Interruption Frequency Index (SAIFI) measured in interrup-

Table 2.5: 2016 Deviations for Projected Annual Actual Electricity Supply by Source for Ghana power system [19]

Power Plant	Source	Percent Deviation (%)	Contribution to Total Generation (%)
Akosombo	Hydro	+17.3	28.76
Bui	Hydro	+2.2	7.04
Kpong	Hydro	+22.0	5.69
Tico	Gas	-8.1	14.20
Ameri	Gas	-24.4	8.99
Tapco	Gas	-43.5	8.90
Cenit	Gas	-39.6	3.12
SAPP	Gas	-84.5	2.79
KTPP	Gas	-81.2	1.49
TT1PP	Gas	-63.5	1.33
TT2PP	Gas	-41.8	0.19
MRP	Gas	-93.8	0.02
T3	Gas	0	0
Karpower	HFO	+58.7	13.90
Trojan	Diesel	100	0.29
Imports	Mixed	+475.1	3.31

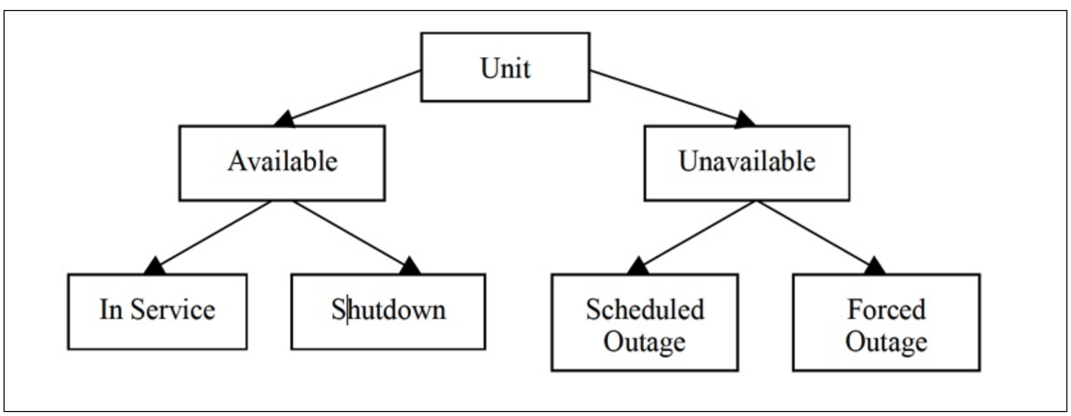


Figure 2-7: Generating Unit States [4]

tions per customer: this index is a measure of the number of interruptions a customer experiences in an operational year. Ghana's maximum SAIFI is 6 across all operational areas [18].

- System Average Interruption Duration Index (SAIDI) measured in hours per customer: this index measures the average duration of interruptions recorded per distribution system during an operational year. Ghana's maximum SAIFI is 48 hours, 72 hours and 144 hours for metro, urban and rural operational areas respectively [18].

- Cumulative Average Interruption Duration Index (CAIDI) measured in hours: this index measures the average duration of interruptions for customers interrupted during an operational year. It is $SAIDI/SAIFI$ and the standard is 8 hours, 12 hours and 24 hours for metro, urban and rural operational areas respectively [18].

- Reserve margin for generation capacity, measured in proportion of total installed capacity: this is the amount of unused available capacity as a percentage of total capacity. The recommended margin is 20-25%, but Ghana's power system has historically operated between 0% and 10%, far below this requirement [42].

- Transfer capability for transmission capacity. Firm transfer capability states how much dependable energy can be transmitted from one node to another over the transmission and distribution network [5, 42]

Figure 2-8 shows the actual performance of Ghana's power system against the system's reliability standards. The yellow bars represent the target reliability standard

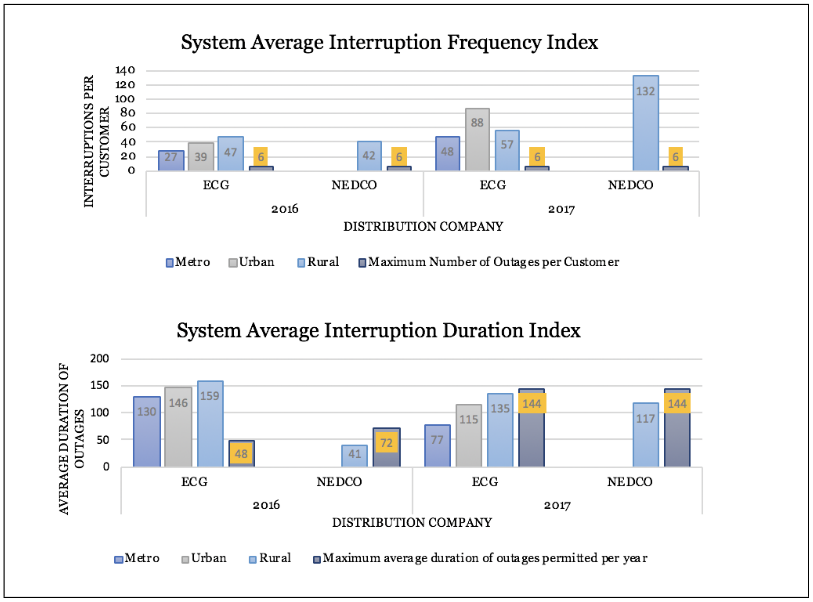


Figure 2-8: Summary of reliability in Ghana's power system 2016 - 2017

and the figure shows that the system consistently failed to meet these standards in 2016 and 2017.

2.6.2 Fuel Supply and Reliability

Ghana's power system reliability and resilience is strongly tied to fuel supply issues, especially natural gas shortages. Historically, gas from the West African Gas Pipeline (WAGP) was the main supplier to power producers. **Figure 2-9** shows the WAGP pipeline route, which starts from Lagos, Nigeria and supplies gas to Benin, Togo, and Tema and Takoradi in Ghana. The WAGP began gas delivery in 2009, but its supply to Ghana was eclipsed by domestic gas supply starting in 2015 (see **Table 2.3**). Yet, despite Ghana's growing domestic gas supply, which is located in Western Ghana, power producers in the Eastern part of Ghana, home to major load centers, have been unable to take full advantage of this resource. This is due to limited gas pipeline

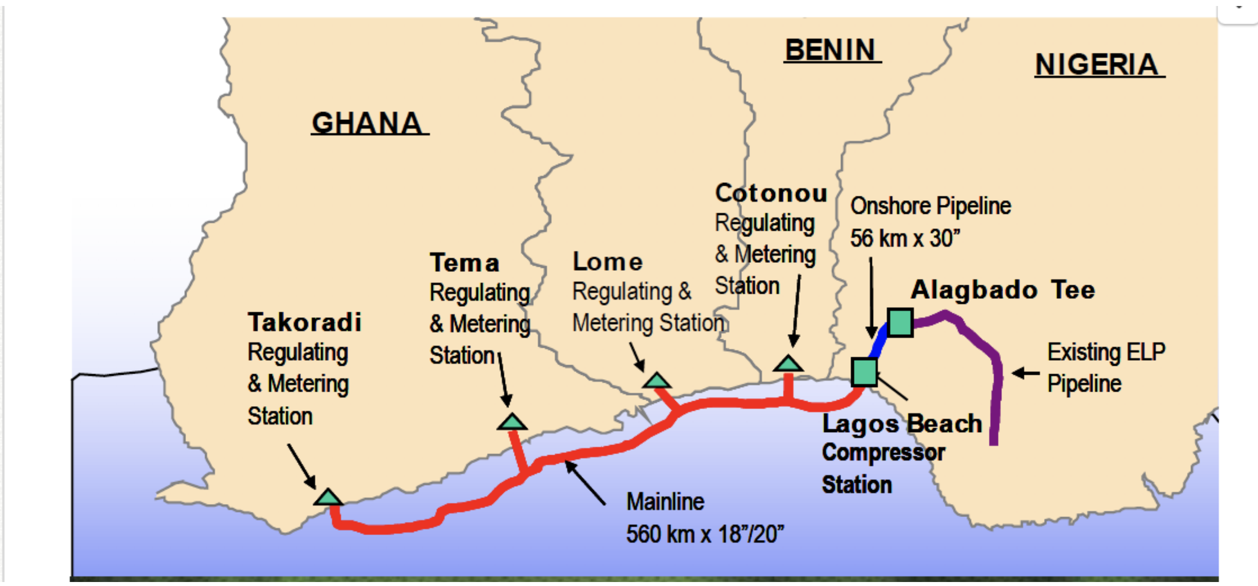


Figure 2-9: West African Gas Pipeline for Gas Supply to Ghana [5]

infrastructure. Furthermore, projections suggest that domestic gas supply will not meet gas demand beyond 2023, and demand for gas in the Aboadze enclave, which is home to a number of large gas-fired power plants, will exceed domestic gas supply by 2035 [5]. Ghana's 2018 Integrated Resource Planning Document stated, "Natural gas has been playing, and is expected to play, an important role in Ghana's power sector, but it has gotten off to a poor start in terms of reliability. Ensuring reliable gas supply has become a key concern for power planners..." [5]

2.6.3 Disparities in Service Quality and Reliability in Ghana

Beyond the technical and regulatory aspects of reliability, it is important note the disparity in reliability across different customer classes. Aidoo and Briggs, in their study on electricity availability across 32 neighborhoods in Accra, argue that due to political and economic factors, blackouts tend to be concentrated on Ghana's poorer communities [6]. They show that poorer people in Accra, Ghana's capital city, tend to experience lower electricity supply than richer people. They also pointed out the quote by Dr. Charles Wereko-Brobby, former Chief Executive of the VRA, the state-owned utility, "The only (power outage) schedule that matters is where ECG thinks it will get paid," which suggests this discrepancy may be intentional [59]. **Figure 2-10** shows load shedding across neighborhoods in Accra from April 28 to May 11, 2015. We see that the higher-income neighborhoods (Cantonments and Ridge), which are highlighted in blue, experienced much more reliable and stable electricity services compared to the two lower income neighborhoods (Chorkor and Maria (Auntie Aku)), which are highlighted in red. Subsequent analysis also showed the strong correlation between electricity reliability and the wealth of a neighborhood. These issues of fuel supply and disparity in service quality across neighborhoods give some insight into the causes and impacts of unreliable electricity service.

2.7 Integrated Resource Planning

Addressing all of the issues raised above around meeting short- and long-term reliability goals, preventing future supply shortages, designing appropriate tariff systems, etc. requires a robust planning framework. Planning for the future helps safeguard against events that may have large-scale impacts [7, 33].

At the same time, it is important to note the limitation of long-term planning methods. Planning typically involves forecasting the future based on historical trends and expected assumptions about economic growth and development, which are rarely accurate. For example, many resource plans are developed using scenario analysis, as is used in this work as well, and the reality might often not fall under any of the

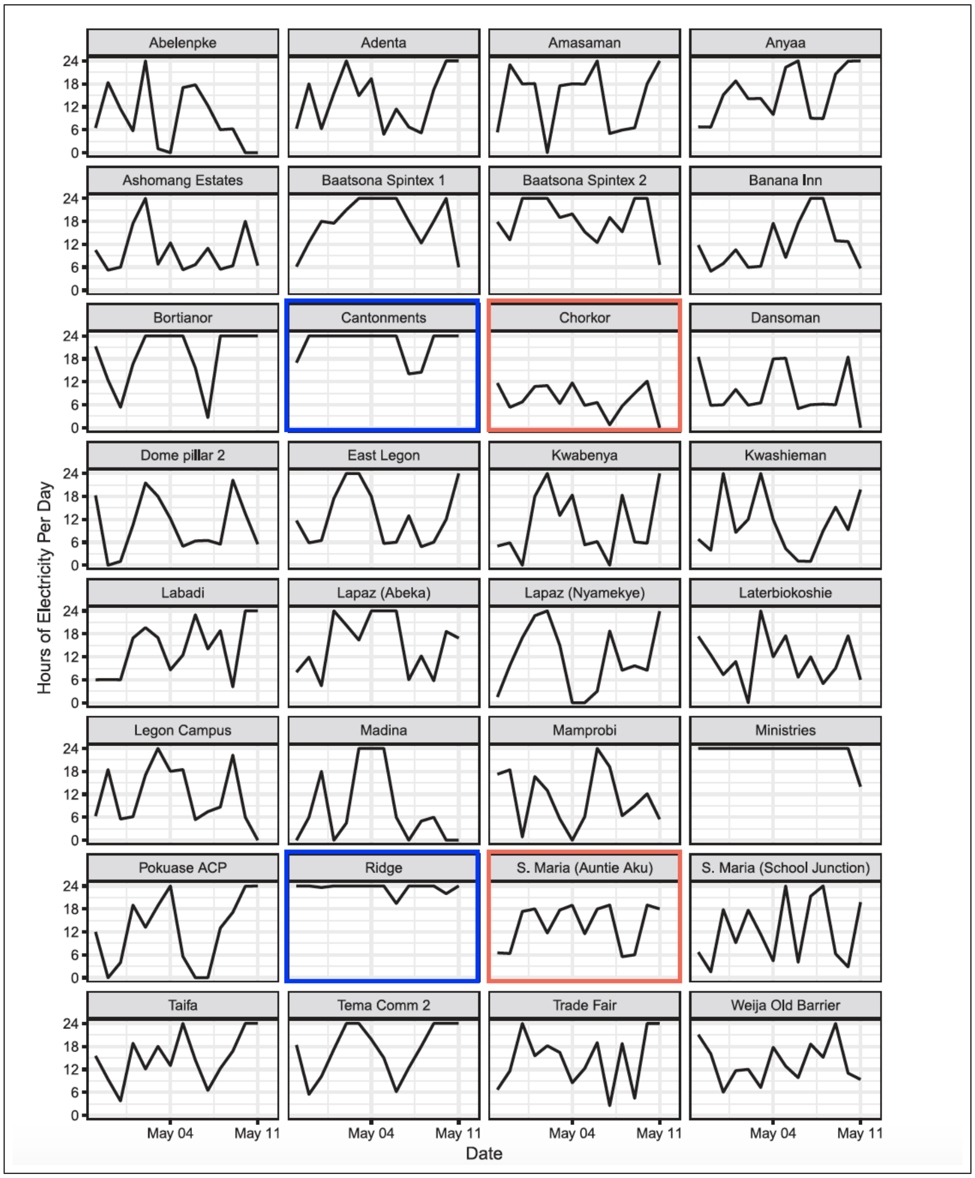


Figure 2-10: Load shedding across neighborhoods in Accra, Legend: Blue - wealthy neighborhoods, Red - Low-income neighborhoods [6]

modeled scenarios. Emerging methods such as flexible planning and decision making under uncertainty tools allow decision makers to make optimal decisions while considering the uncertainty and range of outcomes in the future [60, 61]. Nevertheless, despite the inherent uncertainty in predicting the future and planning for it, long-term electricity planning remains very important because it defines a range of needs and the state of existing capabilities and deficiencies.

One of the mainstream ways of long-term electricity planning is Integrated Resource Planning (IRP). An IRP is usually developed by utilities or the grid operator and lays out how they plan to meet forecasted energy needs through both supply-side and demand-side options [7]. **Figure 2-11** by Wilson et. al (2013) shows the typical flow and decision making chart in the IRP process [7].

The main case for an IRP is that it provides the lowest cost path to meet energy needs, which is beneficial to both consumers and investors. Procedures for entering the electricity market as an investor can be especially tedious, so providing long-term signals through IRPs gives the necessary lead time to develop the appropriate energy projects. Furthermore, IRPs usually include generation pathways that meet energy and environmental policies. For example, hypothetically, an IRP that incorporates Ghana's 10% by 2030 renewable energy target would highlight the lowest cost path to meet that policy and quantify the baseline capacity needed in renewable energy generation. This would then attract investors interested in renewable energy technologies (RETs). An IRP also includes plans to mitigate issues such as fuel shortages and high forced-outage rates to outline a practical cost path that meets reliability standards.

In this chapter, I began by discussing how Dr. Nkrumah's quest for energy indepen-

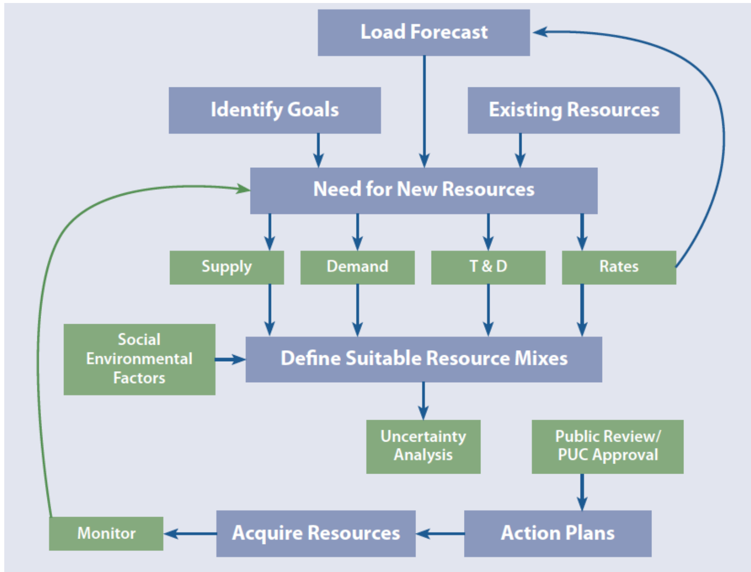


Figure 2-11: Flow Chart for Integrated Resource Planning [7]

dence led to the development of the Akosombo dam. Then I gave some background on the current state of power generation - the recent power crises, various generation sources, the role of the domestic petroleum sector in power generation, and the added complexity of achieving universal energy access. I concluded this chapter by discussing how poor adherence to existing reliability standards during and after the 2012-2016 crisis affected service quality, and resulted in power outages that disproportionately affected lower-income neighborhoods in Accra. In the next chapter, I discuss the role of finance in power generation investment decisions.

Chapter 3

Financing Power Generation Infrastructure

In this chapter, I examine the role of finance and financiers in reducing the power infrastructure gap in Sub-Saharan Africa. Specifically, I discuss the power dynamics between the major financiers of energy infrastructure in Africa, focusing on China's role in Africa's energy sector, the role and potential drawbacks of Public-Private Partnerships (PPPs) in infrastructure development, and how multilateral banks are using finance to shape power generation investment options.

3.1 Financing Energy Access

The scale of the energy access challenge in SSA is enormous, with over 600 million people without electricity access. Electricity infrastructure is particularly capital intensive with regard to power generation and transmission infrastructure. To meet the massive infrastructure gap, worldwide spending on infrastructure between 2016 and 2040 must hit $94 trillion [62, 63]. Africa specifically must increase its infrastructure financing by 40% to bridge the infrastructure gap [64]. Thus, governments have important decisions to make in terms of which projects to pursue, the mix of private and public investment and how they should be managed, operated and regulated. For developing countries such as Ghana, foreign aid is critical in developing infrastructure to meet energy needs. Inviting foreign actors into the decision-making process expands the web of power dynamics, flows of expertise and the competing interests at play. Western powers have historically attached conditions to their aid, such as the existence of democratic institutions and opening up the economy. However, in the last two to three decades, non-Western donors such as China, India and Saudi Arabia have emerged as alternatives to the Western model of foreign aid and investment.

3.2 Chinese Footprints, Climate Change and Western Donors in Africa's Energy Future

In less than a decade, China has become Africa's most important trade and investment partner, especially in the energy sector. As seen in **Figure 3-1**, Africa was the largest recipient of Chinese energy finance in 2018, receiving $4.8 billion in loans to mainly develop coal and hydropower plants [8]. Back in 2013, Ghana was one of the first African recipients of Chinese funding for energy projects with its financing of the Bui hydroelectric dam [37]. At its commissioning, it was China's most sizable investment in Ghana.

Officially, the triple aim of China's foreign policy, deemed win-win-win for all par-

Row Labels	2008-2012 average		2013-2017 average		2018	
	Loan Amount (USD Million)	Percent Total	Loan Amount (USD Million)	Percent Total	Loan Amount (USD Million)	Percent Total
Africa	1,154	7%	5,743	20%	4,775	55%
Europe/Central Asia	8,397	50%	6,009	21%	1,000	12%
LAC	3,047	18%	8,990	31%	600	7%
Middle East		0%	618	2%		0%
South Asia	1,890	11%	4,514	16%	1,646	19%
Southeast Asia	2,432	14%	3,102	11%	599	7%
Grand Total	**16,920**	**100%**	**28,976**	**100%**	**8,620**	**100%**
BRI Countries	**14,438**	**85%**	**20,156**	**70%**	**8,020**	**93%**

Figure 3-1: Geographical Distribution of Chinese Development Finance in Energy [8]

ties, is expanding profit of SOEs, development aid, and strengthening ties with the continent. In a conversation with Howard French, detailed in his book, 'China's Second Continent', a Chinese investor rebuffs claims of neocolonialism remarking: "In China we want to establish win-win relations with African countries. We do not seek to become colonizers. We respect their sovereignty and we do not interfere in their internal affairs" [65].

Research suggests important differences and similarities between the development models of China and the West [41, 66]. Multilateral banks, such as the World Bank and the International Monetary Fund (IMF), have generally followed the Western model. First, similar to Western donors, China gives more development aid to countries who align with it politically in terms of its one-China policy and other UN and international voting issues. Yet in stark contrast to the Western model, it maintains a non-interference approach and pushes against using primarily concessional loans to finance development projects. This non-interference approach has the benefit of allowing beneficiary countries to define the dimensions of projects. This laxity has empowered African politicians to bias the siting of large infrastructure projects to favor political strongholds. In contrast, politicians cannot bias the location of World Bank funded projects [67]. However, in response to the China model, the World Bank is now attaching fewer conditions to developing countries, which allows for more flexibility in infrastructure development. Despite these different approaches to development aid, both models are shown to impact developing countries' GDP equally [66]. Additionally, as the Hannam (2016) study of China and the landscape of power sector governance in the developing world revealed, the United State's Power Africa Initiative was largely in response to China's growing foothold in power sector development in Africa [41].

Chinese investment in fossil fuel-based projects such as coal power plants in Africa represents another departure from the investment direction of other foreign aid partners and multilateral banks. With growing concern about mitigating climate change, energy access efforts are increasingly focusing on the role of renewables in energy sector development. This adjustment in priorities has been observed in the financing decisions made by the region's largest development partners. At the centralized grid level two important trends have occurred since 2005. First, China heavily financed large hydropower projects in Africa and, more recently, coal projects, notably in Eastern and Southern Africa. Second, as seen in **Figure 3-2**, multilateral banks like the African Development Bank (AfDB) and the World Bank (WB) have redirected financing for fossil fuel power plants to renewable energy technologies (RETs) like hydro, solar and wind [9, 41]. Between 2006 and 2010, almost 4.5 GW of fossil fuel power projects were financed by AfDB, but between 2011 and 2015, although overall financing levels decreased, hydro and non-hydro renewables formed the bulk of all

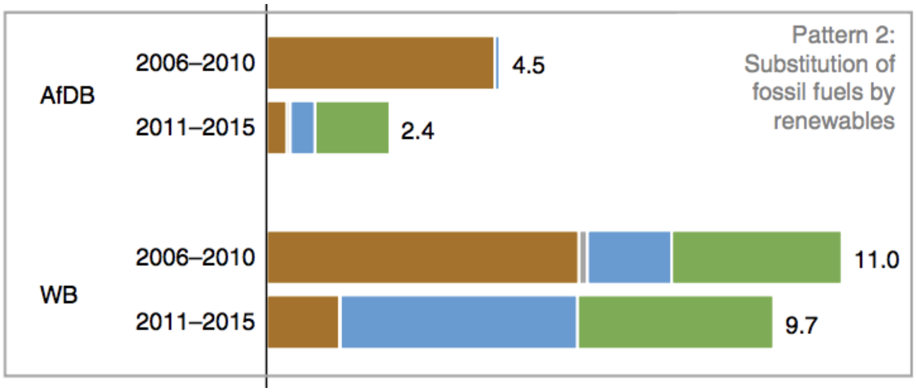


Figure 3-2: Total Financial Commitments to Power-Generation Technologies by AfDB and WB (2006-2015) [9]

financing by the AfDB. The incentive to focus on renewables also depends on who the multilateral banks are partnering with. With public sector partners in donor countries, local authorities typically decide on the choice of project and technology, and usually choose fossil fuel projects. With private partners, project developers only have to meet the banks' investment criteria and recent investments have largely been in renewable energy projects [9, 41].

3.2.1 Financing Power Generation in Ghana

In the case of Ghana, interviews with energy planners in the country reveal some frustration in the shift of funding from fossil fuel technologies to RETs, which has caused them to look elsewhere for funding [1]. Some of these planners view this shift as the West trying to coerce the developing world to adopt their preferred pathway to development. In their view, this redirection of funds by Western multilateral banks and the AfDB is to the detriment of Ghana's power sector development. **Table 3.1**

[1]This was revealed during an interview with Gökçe Gunel, a Tenure-Track Assistant Professor in the School of Middle Eastern and North African Studies at the University of Arizona, who is currently writing a book on floating powerships in Ghana

Table 3.1: Renewable energy investment targets by 2022 [2, 20, 21]

Energy Source	Exploitable potential (MW)	Investment requirement (million US$)	Installed capacity at 2018
Solar	20	100-150	31
Wind	300	250-400	0
Biomass	90	90-150	0
Medium and small hydro	150	200-300	0
Total	560	640-1000	31

shows the significant financial investment required in Ghana's renewable energy sector, which suggests foreign investment will be key to the growth of this sector.

Beyond multilateral banks, developing countries have also increased engagement with each other. Recent years has seen a growth in South-South technology and knowledge transfer, and funding of developing projects. South-South collaboration refers to the engagement between countries in the Global South, most of which are developing countries. Analysis by Steffen et. al (2019) showed that the investment portfolios of public sector branches of 'South-South' development banks, which are banks that aim to increase cooperation within the developing world, have an especially small fraction of non-hydro renewables [9].

Though these engagements are heavily influenced by China's efforts to offload excess coal capacity, equipment and technology, this new direction has also paved the way for engagement with other countries and development partners [9]. The U.S. provided funding for some thermal generation plants through the $498 million compact from the Millennium Challenge Corporation (MCC). Other countries have also stepped in to help with power generation projects. These countries, notably Turkey, have used similar language as China in positioning their investment and engagement as one with no strings attached unlike that of Western partners. Such engagements, which often occurs at the highest political level, essentially bypass the official systems in place for power generation projects in Ghana. As such, projects financed by certain investors can have an expedited project cycle. Notable examples include:

- AKSA Enerji Uretim AS (AKSA) 370MW project: In 2018, Parliament waived the $27 million tax tag of the project under the terms of an Emergency Power Agreement (EPA) even though the power crisis supposedly ended at the end of 2016 [68]. This project, developed by Turkish investors, is supposed to support efforts to diversify the power generation fuel mix even though it runs on expensive heavy fuel oil.

- During the 2012-2016 crisis, the government interfered with the electricity planning process by directly procuring emergency generation plants from Turkey and the United Arab Emirates (UAE) in the form of:

  - The 450MW two-phase Karpower Barge project: A 20-year power purchase agreement (PPA) was signed with phase 1 (225 MW) completed in 2015 and the second phase arriving in 2018. It initially ran on expensive liquid fuel, but can now operate using natural gas. Even though the government stated that this plant was procured to meet short-term emergency needs, Karpower's Africa and Asia Director stated in 2015 that "The powerships are not to address Ghana's short-term emergency need. The powerships would rather bridge the gap in Ghana's quest to find sustainable means of power supply..." [29]

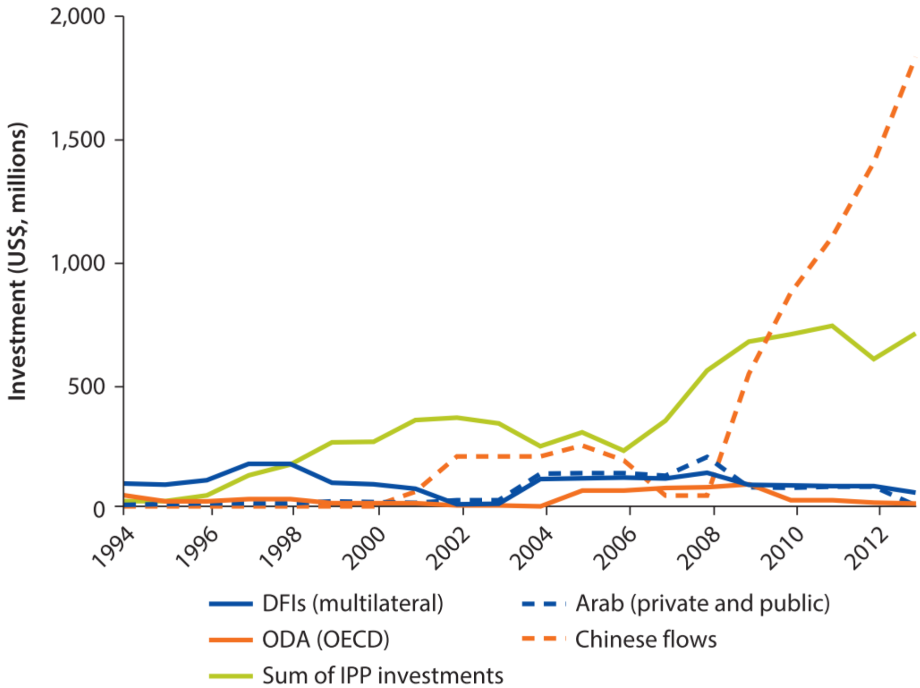
  - The 250MW Africa & Middle East Resources Investment Group LLC (AMERI) project: A $510 million project that was built in 4 months and negotiated during the peak of the crisis. This deal received intense scrutiny due to the Ghanaian government's subsequent assertion that the deal project was severely overpriced. Terms of the power purchase agreement (PPA) have been renegotiated at least two more times.

These projects are just a few examples of how politics and politicians can influence power generation investment decisions. Since 2008, over 90 provisional licenses for RETs and 60 for non-RET power plants were granted in Ghana. Yet, only a handful were actually developed and that can be partly attributed to the arduous process that independent power producers (IPPs) have to go through in the project life cycle. Consequently, access to individuals and institutions like the China ExIm Bank or the Turkish government can provide a fast-track basis to essentially leapfrog due process.

3.3 Public-Private Partnerships for Power Generation

Beyond considering power generation projects, other aspects of foreign aid can affect the financial viability of utilities operating in developing countries. One of these is the emergence of the Public-Private Partnerships (PPPs). The Government of Ghana, for example, recently signed a 20-year PPP with the Manila Electric Company (Meralco) for the operation and management of the Electric Company of Ghana. **Figure 3-3** shows that in the past decade, the private sector has become a major investor in power generation in Sub-Saharan Africa.

PPPs are cooperatives between public institutions and private actors to develop a



Source: Compiled by the authors, based on various primary and secondary sources.
Note: Ghana's Kpone IPP and Nigeria's Azura investments in 2014 and 2015, respectively, which together total $900 million, will result in a continued upward tick in IPP investments. DFI = development finance institution; IPP = independent power project; ODA = official development assistance; OECD = Organisation for Economic Co-operation and Development.

Figure 3-3: Investment in Power Generation: Sub-Saharan Africa (Excluding South Africa), 1994-2013 [10] project, usually some kind of public sector infrastructure project over the long-term. Core to the success of PPPs is answering questions about affordability, risk allocation and bankability (i.e. project financing). Additionally, there must be a clear agreement on expected project outcomes. Outcomes must be specific, measurable, achievable, realistic and timely [69]. Reviewing some past PPPs across different political, financial and social contexts shows the World Bank's apparent preference and imposition of PPPs as a model of developing infrastructure. Evidence suggests that the WB's approach towards project development mirrors that of its major funders, especially the United States, which historically had a pro-privatization stance. The U.S. has the largest voting share and routinely influences World Bank policy by invoking legislative power through the U.S. Congress. In 2013, the Obama administration launched the Power Africa Initiative, a public-private initiative to address the large electricity access gap in Africa. As part of efforts to prioritize this new turn in the U.S.–Africa relationship, the Doing Business in Africa (DBIA) campaign was launched in 2014 to facilitate U.S. business activity in Africa, and the Millennium Challenge Corporation launched the Public-Private Partnership (P3) Platform with the aim of supporting the delivery of such projects in Africa. This shift to PPPs by the U.S. was echoed in the WB finance document, "Guidance for PPPs".

Though outcomes from PPPs in the developing world remains understudied, emerging evidence suggests negative impacts of PPPs on the most vulnerable populations [70, 71]. While PPPs can deliver efficiency improvements and address critical infrastructure needs, projects are often poorly designed to the specific location and may have adverse environmental impacts, worsen political instability and negatively impact the poor, which is contrary to the WB's mission of reducing poverty and inequality [70]. Heinrich-Boll-Stiftung's comprehensive legal analysis of the Bank's

Guidance on PPPs found that it does not allocate risk equally and punishes the state if it attempts to regulate environmental and social issues. Additionally, it does not classify civil wars as force majeure events even though civil wars cripple economies and its occurrence is usually beyond the control of one political actor. The language in the Guidance, which is a benchmark for developing PPP contracts, seemingly prioritizes risk management for the investors rather than balancing investor interests and with those of the state and consumers.

Furthermore, even though PPPs have been lauded as a silver bullet to the infrastructure finance gap in Africa, evidence suggests that PPPs are still falling short of expectations. PPP advocates maintain that since private investors' priority is to maximize profit, they are strongly incentivized to operate as efficiently as possible. Yet operating in sectors like electricity and transportation offer huge upside, but significant risk in the form of demand risk and the risk of political inference, which can quickly derail the financial viability of a project. The European Court of Auditors assessed 12 large European PPPs and concluded that "EU PPPs suffer from widespread shortcomings and limited benefits" and with losses of $1.8 billion could not be regarded as economically viable [71]. PPPs have attractive benefits, but if risks are badly managed, all parties, including the state and by extension consumers, end up incurring these costs. Information asymmetries and pervasive corruption also occur in PPP contracting. In developing the Bujagali Dam in Uganda, an initial and cheaper PPP offer was thrown out due to push back from environmentalists and local communities over social and environmental risks, and cases of corruption and bribery in the contracting process. Ultimately, a PPP, twice as expensive was eventually signed and, due to technical constraints and low domestic demand, the asset is operating far below optimal conditions and has led to increases of up to 151% in electricity costs.

Even in cases where PPPs are successfully developed, an important question is whether they are sustainable since many developing countries have weak institutions with risks of expropriation and renegotiation. In Lesotho, a first-of-its-kind healthcare PPP was successfully established, but the hospital soon faced demand risks due to over subscription of hospital services. This resulted in the state absorbing all the risk and diverting substantial funds from its meager health budget, which was detrimental for this small, developing country. In addition, many developing countries are often below investment grade and so PPPs require credit guarantees from the state. Even if a state provides those guarantees, in the event of a default, the state may be unable to pay back. Additionally, poorly priced PPP proposals might lead to financial loss for the state. Argentina's recent renewable energy PPP proposal might have been too generous given that they received six times as many bids as they needed and they bore a disproportionate amount of financial risk in order to attract investors.

These cases highlight the crux of PPPs and project financing in generation - allocating risks efficiently. The current framework used in assessing risk are Public-Private Comparators (PPCs). Comparators are a useful tool in assessing the competitiveness of bids, yet the mechanics fare poorly in developing countries. This framework requires existing competitively priced projects in order to use benchmarking as well as skilled personnel to assess the value of bids. Many developing countries in Africa fail to meet both conditions.

Developing a competitively priced PPP can be especially tricky in the case of unsolicited or sole source bids. Often, a developing country receives a sole bid or directly petitions investors for a specific project and there are few resources available to assess the bid's competitiveness and 'fairness'. It might then take a few tries to obtain competitive bids, which ultimately leaves the consumers financially responsible for poor investment decisions by the government.

Finally, of increasing concern in the midst of growing PPPs is the growing debt burden of many African countries. Most of Africa's debt is held by private banks, bondholders, and development banks. In October 2017, finance ministers of low-income Francophone countries called on the World Bank to publish the true costs of PPPs to ensure they do not bypass normal budget procedures and lead to intergenerational debt transfer. The problem is not that PPPs are inherently poor investment decisions for the state, but that many developing countries lack the strong institutions and regulatory framework to support this kind of development model. PPPs, in their current form, are not designed to address risks, concerns and institutional shortcomings.

Financial, technological, operational and political deficiencies have undercut some attempts to repair the system, yet ongoing reform attempts suggest a strong desire to turn the situation around. In recommending options for structural and institutional reform, it is critical to specify the exact problems facing the sector and consider private sector engagement within the country's political and economic context.

3.3.1 Public-Private Partnerships in Ghana

PPPs in Ghana's power sector mainly take the form of partnerships between the country's main electricity off-taker, ECG, and independent power producers (IPPs). The six major IPPs operating in Ghana account for 40% of all generation. In her extensive work exploring PPPs in Ghana's power sector, Issifu showed that the lack of financial guarantees between IPPs and ECG, and the failure of ECG to make timely payments to IPPs have resulted in a lack of trust between the two parties [72]. Specifically, during the height of the 2012-2016 power crisis, ECG consistently defaulted on payments to Sunon Asogli and CENIT, two major IPPs that began operating in 2011 and 2013 respectively [72]. Due to long-running profitability issues, ECG, a state-owned entity, seemingly exploited their position as the only electricity distribution company in Ghana's major load centers to default on electricity service payments to them [72].

Since its operations directly affect the profitability of all the other value chains in Ghana's power sector, ECG's profitability has long been a focus of power sector reform in Ghana. As such, effective March 1 2019, ECG entered into a 20-year concession agreement with Power Distribution Services (PDS), which granted PDS control over ECG's investment decisions, and management and operation of its assets [45]. However, without a holistic reworking of power generation planning in Ghana, this move could fail to substantially alter the economic health, system reliability and resilience of the grid.

Eberhard et al. outlined many factors at the country and project level that contribute to successful IPP investments, and by extension PPPs in SSA [10]. These include coherent power sector planning, competitive bidding practices at the country level, and creditworthy off-takers and secure and adequate revenue streams at the project level. The concession agreement is an attempt to make ECG creditworthy and a secure and adequate revenue stream. Yet, without equal emphasis on capacity expansion planning, rate design, and shifting from bidding practices that clearly favor powerful foreign donors and strategic partners like China, Turkey and the United

States, Ghana's power system is unlikely to operate efficiently.

In this chapter, I examined the role of finance and financiers in the form of multilateral banks, development partners like the U.S. and China and independent power producers in power generation to show that capacity generation planning cannot be successful without paying attention to the motives, instruments and value of external financial investors and donor countries. In the following chapter, I summarize my findings of a literature review on the role of capacity expansion models for electricity planning as well as its use in exploring how system constraints, such as energy and environmental policies and fuel supply, shape technology options and influence Ghana's generation expansion pathway in the short-to-medium term.

Chapter 4

Approaches for Electricity Planning in Sub-Saharan Africa

Electricity has unique characteristics which make systems planning much more complex compared to other goods. Except for energy storage technologies, like pumped hydro storage, electricity largely cannot be stored, and so it must be generated, transported and consumed in real time. Simply, generation must always equal load [3]. Electricity flows also cannot be directed, and a disturbance to one node in the network can result in disruptions across the network. A typical power system consists of four main components: generation, transmission, distribution and retail. In the early days of the electric grid, most power systems were vertically integrated, and one body operated and oversaw all four functions. Now, most of the power systems around the world are horizontally integrated, meaning the four value chains operate independent of each other [3]. As seen in **Figure 4-1**, this is not the case in most of SSA, as most electricity sectors remain vertically integrated and under govern-

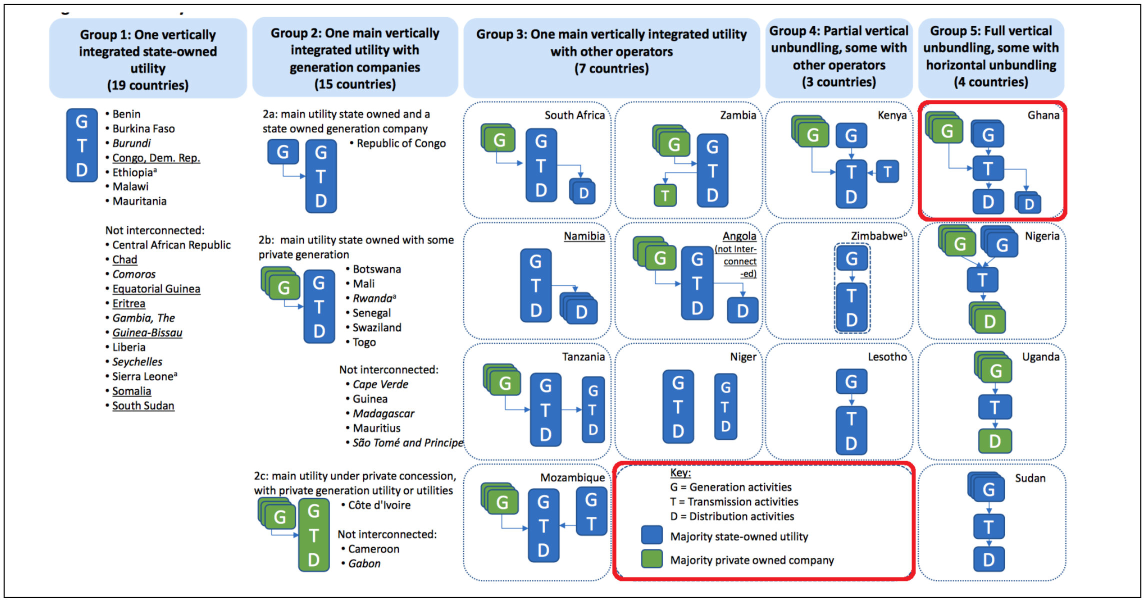


Figure 4-1: Electricity sector structures in Sub-Saharan Africa [11]

ment control [10, 11]. As such, there is much more interaction between government (and politics) and energy planning. Ghana's power sector is horizontally integrated to some degree. Even though the four functions remain under government control, IPPs now play a prominent part in power generation. Another unique characteristic of electricity is that parts of the value chain operate as natural monopolies. A perfectly competitive market can be inefficient for some goods because many firms in the market actually lead to an overall increase in prices of the good or service. Electricity transmission and distribution often fall into this category of natural monopolies because networks are capital intensive and benefit from large economies of scale, and monopolies of these functions benefit from spillover effects like increased coordination and uniformity in service provided [3]. Distributed energy resources (DERs) may change the prevalent electric market structure and business models, but in the case of Ghana, it still largely operates transmission and distribution as natural monopolies and regulates their activities.

These characteristics of electricity make systems planning particularly difficult. As such, quantitative models of the various system components are beneficial and can help decision-makers better plan for the future. In this chapter, I summarize findings of a literature review on power sector planning in SSA.

4.1 Power Systems Modeling

Power systems modeling, particularly capacity expansion modeling, is a common approach for electricity planning. Trotter et. al (2017) defines electricity planning as "an integrated approach of analyzing an economically, technologically, environmentally, socially and/or politically suitable equilibrium between electricity demand of a given unit of analysis and different available supply options across at least one element of the electricity value chain" [33]. Power systems modeling takes a quantitative modeling approach to assess various aspects of the power system, such as capacity expansion, dispatch and/or transmission and distribution. Context-specific power sector modeling can help explore generation expansion pathways. Most models require significant temporal and spatial data, which is rarely publicly and readily available or reliable in countries with underdeveloped grids [73]. Recent studies have begun to use various modeling approaches for generation expansion planning relying on insufficient or restricted access to data [73]. In this thesis, I devoted significant effort to engagement with stakeholders, and data collection and processing in order to obtain robust and reliable data on Ghana's power generation.

4.1.1 An Overview of Power Systems Modeling

Power systems models include a wide of array of models, which cover various components of electricity decision-making, at various time scales. In general, the time scales considered are the long- term, the mid-term and the short-term. Long-term planning (i.e. capacity expansion planning) involves multi-decade planning that signals the projected generation expansion pathway to public and private sector stakeholders. Mid-term planning involves annual planning for fuel procurement, maintenance and hydrothermal coordination. And short-term planning involves unit-commitment decisions, hourly scheduling, economic dispatch, and real time operation [3]. The growth of RETs, which are intermittent and highly variable resources, has required large improvements in short-term operational planning in order to include highly resolved temporal and spatial characterizations of renewable resources. RET's declining costs have also impacted the accuracy of long-term resource plans, usually resulting in the overrepresentation of oil and gas and the underrepresentation of renewables [3]. For each time scale, a plurality of models and technical approaches are used to explore "optimal" decisions.

Analysis involving optimality usually employs optimization tools. Under a single-criteria mode, the objective function of a short-term optimization formulation usually finds the cost-minimizing scheduling for all generation units that meets system demand, and satisfies technical and non-technical system constraints. At the short-term level, this process is iterated to inform second-by-second economic dispatch decisions and requires a continuous exchange of information between the system operator and generator operators. Additionally, to protect against unexpected voltage drops, load swings and loss of generation, short-term operation allocates dispatchable spinning reserves.

Mid-term generation planning follows a similar optimization framework with the objective of minimizing cost in the medium term (usually a year) subject to all the system's constraints. This type of analysis provides details on production and operation costs for budgeting and planning purposes. For both the system planner and generating unit, information on fuel consumption and hydrothermal coordination (especially important in hydro-rich generation mixes) allows for setting tariffs, and budgeting and procurement respectively [3]. The input data for such optimization tools are forecasts, so this level of planning often has a higher degree of uncertainty as data such as electricity demand, renewable generation, fuel costs and natural inflows of hydro systems might be subject to uncertainty that could significantly affect the optimal operation bundle [3].

Long-term planning also follows a similar framework of minimizing system costs while meeting projected demand. It is typically referred to as capacity expansion planning, and involves identifying the optimal types and timing of investments in new generation capacity. Input data consists of future projections of critical factors, such as demand, resource potential and technology and cost characteristics of various generating units [3].

4.1.2 Previous Long-Term Electricity Planning Efforts by Ghana

In 2006, Ghana released a comprehensive long-term energy plan, SNEP, to meet its energy needs till 2020 [12]. The plan for the electricity sub-sector was in the form of a 2006-2020 generation expansion pathway under three scenarios:

- Scenario 1: Thermal Generation + 10% non-hydro renewables by 2020
- Scenario 2: Thermal Generation + 10% non-hydro renewables + Hydropower

POWER PLANTS	2005	2006	2007	2008	2009	2010	2011	2012
a. Akosombo Hydro	1,020	1,020	1,020	1,020	1,020	1,020	1,020	1,020
b. Kpong Hydro	160	160	160	160	160	160	160	160
c. Tapco_oil	330	330	0	0	0	0	0	0
c. Tapco_gas		0	330	330	330	330	330	330
d. Tico_oil	220	220	0	0	0	0	0	0
d. Tico_gas		0	220	330	330	330	330	330
e. Tema diesel	30	0	0	0	0	0	0	0
f. Wind turbines				50	100	160	160	200
g. Effasu Power gas Barge	125	125	125	125	125	125	125	125
h. Tema 330 MW gas thermal				110	220	330	330	330
h. 2nd Tema 330MW gas thermal							0	0
i. Embedded Generation - gas turbine								
j. Bui Hydro at 200MW							200	200
k. 2nd 660MW CCGT at Takoradi								
l. Biomass, solar, minihydro, etc			1	5	6	6	7	7
m.Municipal solid wastes								
n.Landfill power								1
Total	**1,885**	**1,855**	**1,856**	**2,130**	**2,291**	**2,461**	**2,662**	**2,703**
VRA expected Import	***100***	***200***	***200***	***0***	***0***	***0***	***0***	***0***

Legend
Green: ***No installation***
Yellow: ***Standby - back up / reserve installations. Or yet to be connected to the grid.***

Figure 4-2: Scenario 2 2005 - 2012 Generation Expansion Pathway [12]

from the Bui Dam by 2020

- Scenario 3: Thermal Generation + 10% non-hydro renewables + Hydropower from the Bui Dam + Nuclear by 2020

Figures 4-2, 4-3 and 4-4 summarize the expansion pathways under these three scenarios. Despite the generation expansion pathway options shown in these figures, the actual generation expansion pathway since 2006 has been starkly different. Two power crises in 2007-2008 and 2012-2016 shaped generation investment decisions, as discussed in chapters 2 and 3. Thus, in 2016, installed capacity of non-hydro RETs stood at 42.5 MW (all from solar) compared to the 380 MW projected, the Bui dam was completed in 2013, and thermal generation accounted for close to 70% of generation unlike the 52% projected under scenario 2. Additionally, even though the generation path projected no diesel power plants in operation, diesel generation, in

POWER PLANTS	2013	2014	2015	2016	2017	2018	2019	2020
	Installed Capacity in Megawatts (MW)							
a. Akosombo Hydro	1,020	1,020	1,020	1,020	1,020	1,020	1,020	1,020
b. Kpong Hydro	160	160	160	160	160	160	160	160
c. Tapco_oil	0	0	0	0	0	0	0	0
c. Tapco_gas	330	330	330	330	330	330	330	330
d. Tico_oil	0	0	0	0	0	0	0	0
d. Tico_gas	330	330	330	330	330	330	330	330
e. Tema diesel	0	0	0	0	0	0	0	0
f. Wind turbines	200	200	200	200	200	200	200	200
g. Effasu Power gas Barge	125	125	125	125	125	125	125	125
h. Tema 330 MW gas thermal	330	330	330	330	330	330	330	330
h. 2nd Tema 330MW gas thermal	110	220	330	330	330	330	330	330
i. Embedded Generation - gas turbine			120	120	120	120	120	120
j. Bui Hydro at 300-400MW	300	300	300	300	300	300	300	300
k. 2nd 660MW CCGT at Takoradi						110	220	330
l. Biomass, solar, minihydro, etc	7	10	10	10	15	15	20	25
m.Municipal solid wastes	20	40	80	100	120	120	140	140
n.Landfill power	2	4	4	5	8	11	11	15
Total	**2,934**	**3,069**	**3,339**	**3,360**	**3,388**	**3,501**	**3,636**	**3,755**
VRA Import	***0***	***0***	***0***	***0***	***0***	***0***	***0***	***0***

Legend
Green: ***No installation***

Figure 4-3: Scenario 2 2013 - 2020 Generation Expansion Pathway [12]

the form of back-up generation, actually formed a sizable portion of the mix (12% of generation in 2014). Disparity between actual and projected generation usually occurs with scenario analysis of the future, but it is especially notable that renewables struggled to gain a foothold and expensive diesel generation played a more prominent role than initially envisioned.

4.2 Electricity Planning Tools

This section reviews existing literature on electricity planning tools and implementation in sub-Saharan Africa. Trotter et. al (2017) present an extensive literature review of electricity planning and implementation in SSA, and identifies 42 out of 306 studies that conduct single-criterion optimization. Of these 42 studies, 63% recommend a 100% RET solution, 16% suggest a hybrid mix comprising RETs and

ELECTRICITY EXPANSION PLAN – GENERATION MIX BY INSTALLED CAPACITY 2016 - 2020							
SOURCE	**PLANT**	**OPTION 1**		**OPTION 2**		**OPTION 3**	
		Total	**Percent**	**Total**	**Percent**	**Total**	**Percent**
Hydropower		**1180**	***31.2%***	**1380 (1580)**	***37.8% 41.0%***	**1380 (1580)**	***37.8% 41.0%***
	Akosombo & Kpong	1180		1180		1180	
	Bui hydro 200 MW	0		200 (400)		200 (400)	
Thermal		**2225**	***58.8%***	**1895**	***51.8% 49.2%***	**1565**	***42.8% 40.5%***
	Tapco	330		330		330	
	Tico	330		330		330	
	Tema diesel	0		0		0	
	Effasu Barge	125		125		125	
	330MW Tema GT 1	330		330		330	
	330MW Tema GT 2	330		330		330	
	Embedded Gas Gensets	120		120		120	
	3rd 330MW Takoradi CCGT	330		330		0	
	4th 330MW Takoradi CCGT	330		0		0	
Renewables		**380**	***10.0%***	**380**	***10.4% (9.9%)***	**380**	***10.4% (9.9%)***
	Biomass, solar, minihydro, etc	25		25		25	
	Wind	200		200		200	
	Municipal Solid Wastes	140		140		140	
	Landfills	15		15		15	
Nuclear		**0**	***0***	**0**	***0***	**335**	***9.1% 8.7%***
	Light water reactor – IRIS-335	0	***0***	0	***0***	335	***0***
	TOTAL	**3785**	***100%***	**3655 (3855)**	***100%***	**3660 (3860)**	***100%***

Figure 4-4: SNEP Electricity Expansion Plan for 2016 to 2020 [12]

non-RETs and on-grid and off-grid solutions, and 21% suggest non-RET solutions [33]. Most of the papers reviewed use an either or approach towards renewables versus non-renewables. It is important to note that the overall objective function used in the models significantly impacts final generation mix projections. Usually, models that minimize lifetime cost or net present value find more renewables to be optimal due to their low to non-existent variable operation and maintenance costs (largely due to small/no fuel costs), which offset their significant upfront investments [33]. Furthermore, with the commercialization of off-grid electricity solutions, most studies usually focus on electricity planning for a 1) centralized, 'on-grid' system, 2) off-grid, distributed or mini-grid like system, or 3) a combination of 1 and 2 [33].

4.2.1 Electricity planning tools applied to Ghana

J.K. Turkson (1990) conducted one of the first energy sector planning studies in Ghana in 1990. This work was a largely qualitative exercise to highlight Ghana's growing dependence on oil for basic energy services. Turkson stressed the importance of an energy planning institution and observed that emphasis had long been placed on large hydropower projects, without adequate focus on mini-hydro schemes [74].

Gyamfi et al. (2015) reviewed assessments of potential renewable energy resources, current exploitation status and potential contribution to Ghana's electricity supply, and also explored the barriers to utilization based on the existing policy and regulatory environment. They stated that the three most important factors in selecting new capacity is that it be renewable, locally available at reasonable costs, and environmentally friendly [21]. In contrast, an interview with ECG officials in the wholesale markets team conveyed that cost and dual-fuel capability were the most important factors when making power generation investment decisions in Ghana.

Adom and Bekoe (2015) compared two econometric approaches – an autoregressive distributed lag model (ARDL) and a partial adjustment model (PAM) - and estimated that 2020 electricity demand would be between 20,000 and 35,000 GWh, overestimating demand by close to 20,000 GWh (demand in 2018 stood at 13,000 GWh) [75]. This illustrates the degree to which forecasts can deviate significantly from actual figures.

Abdul-Salam and Phimister (2016) used hierarchical lexicographic programming, a subset of multi-criteria decision analysis to develop an electrification plan for grid extension or off-grid investment in un-electrified communities [76]. The criteria they used were 1) cost efficiency and 2) bias for large populations as a proxy for political votes and a measure of political economy considerations [76]. Though there is a strong case for including political economy considerations in planning efforts, this formulation essentially encodes the perceived existing bias for urban areas over sparsely populated areas in planning efforts.

Diawou and Kaminski (2017) used a short-run linear programming model developed in GAMS to explore how a carbon tax and transition to low-carbon technologies will affect the generation mix [77]. They explored the three generation expansion scenarios in the SNEP. All the scenarios analyzed, with the exception of the scenario with higher hydro generation due to increased rainfall, increased overall generation costs. To attract foreign investment, they recommended adjustments to the tariff structure and increased investment in ancillary services.

Ghana's 2010 SNEP also employed various power systems models. The three main tools used were the Long range Energy Alternative Planning (LEAP), RETscreen, and MESSAGE. LEAP, developed by the Stockholm Environment Institute, is an integrated energy and environmental planning tool used for energy projections. RETscreen, developed by the CANMET Energy Diversification Research Laboratory of Natural Resource, provides a standardized and integrated renewable energy project analysis tool that compares project life-cycle costs and the avoided greenhouse gas emissions obtained through such projects. MESSAGE, developed by the International Institute for Applied Systems Analysis, optimizes the energy system [13, 22, 78, 79].

4.2.2 Tools applied in rest of sub-Saharan Africa

There are other robust capacity expansion planning tools that have been used in SSA. In this section, I focus on two, the System Planning Test model for Africa (SPLAT), and SWITCH (a loose acronym for 'solar, wind, conventional and hydro generation and transmission').

SPLAT was developed based on the MESSAGE modeling platform. It calculates technically and economically optimal pathways for generation and transmission expansion. SPLAT was used to study cross-country trade of electricity in West Africa. In its formulation, each West African country is represented by a node interlinked by transmission lines. Within each node, demand is classified as industrial, urban or rural, and then daily, weekly and seasonal load profiles for each are determined [13, 22]. An important assumption in the model is that renewable energy penetration is limited to 10% and 20% of total generation for solar and wind, due to system reliability concerns. SWITCH is an open-source multi-period stochastic linear programming model that minimizes the present value cost of generation and transmission expansion [80]. Key model assumptions included:

- No hydropower expansion due to insufficiently temporal data. Given that a hydro boom is underway in the region, this assumption might fail to give an accurate picture of the evolution of Kenya's generation mix. In general, the lack of data is a huge barrier in studying the different power systems across sub-Saharan Africa. Very little of the temporally and spatially rich data required is available to researchers that are not directly interfacing with government authorities or energy planners in these countries.

- Exclusion of technologies such as carbon-capture and sequestration and wave/tidal generation, which are still in the demonstration phase. These technologies have not been commercialized despite substantial research and development, and thus it is reasonable to assume that they will not be deployed commercially and at a low enough price point to not feature prominently in Kenya's 2020 to 2035 generation mix.

- No imports or exports to neighboring countries are considered. Even though there is growing electricity transport between borders, for Kenya (as with Ghana), it does not yet form a substantial proportion of the mix.

- Long-term investment decisions are made in 5-year increments

- Dispatch and investment decisions are made by sampling 2304 hours (out of 8760 total hours in a year), which may capture peak demand well but fail to account for energy requirements for continuous months/seasons.

Assumptions such as these can limit the real world relevance of the model results.

4.2.3 Other Electricity Planning Tools

There are many other capacity expansion planning tools that have yet to be applied to SSA. Some of the models include ReEDS, HOMER, PLEXOS and EleMod. ReEDS (the Regional Energy Deployment System), developed by the U.S. National Renewable Energy Laboratory (NREL), is a capacity planning and economic dispatch model for the North American electricity system and designed to capture the regional attributes of energy production and consumption [81]. HOMER (the Hybrid Optimization Model for Electric Renewables) was also developed by NREL and is the most widely used planning tool. It is a micro-power optimization model that helps design off-grid and grid-connected system. It is particularly adept at evaluating optimal generation technology options for small power systems [82]. PLEXOS Integrated Energy Model, developed by Energy Exemplar, is a simulation software primarily designed for energy market analysis [83]. EleMod, developed by the MIT Energy Initiative, is an hourly dispatch and capacity expansion model, originally designed for the U.S [84]. Each of these models has strengths and shortcomings (as seen in **Table 4.1**).

4.3 The need for a new model

Several gaps remain in the capacity expansion literature. First, while many studies have been undertaken for countries in SSA and such studies provide widely applicable strategies for robust electricity planning, it is crucial that more studies focus on country-specific contexts [33]. Second, there is a lack of holistic decision analysis approaches that use both qualitative and quantitative methods to understand electricity planning in larger socio-technical systems. Third, there is a lack of studies

Table 4.1: Comparison of long-term power systems model applied to Sub-Saharan Africa [22]

Tool	Timeseries	Unit Commitment	Operating Reserves	Generator Fuel Switching	Inter-Hour Electricity Storage	Hydro Networks
ReEDS	No	No	No	Yes	No	No
LEAP + OSEMOSYS	No	No	No	Yes	No	No
PLEXOS	No	No	Yes	Yes	No	Yes
SWITCH 2.0	Yes	Yes	Yes	Yes	Yes	Yes
EleMod	Yes	No	Yes	Yes	No	No

using highly resolved and reliable data. As shown in **Table 4.1**, with the exception of SWITCH, most of the widely used long-term electricity planning tools that are publicly available lack the rich temporal and spatial formulation that allows for exploration of the impacts of planning decisions at multiple timescales. Fourth, there is a need to develop electrification plans across all value chains of generation, transmission, distribution and retail. Finally, multi-criteria decision methods are seldom employed.

This thesis addresses the first three gaps by employing quantitative and qualitative methods, and a spatially and temporally rich dataset to explore the impact of recent power generation decisions on bulk generation costs and climate and renewable energy goals in Ghana. The main quantitative method used adapts EleMod, a single-criterion system cost-minimization linear programming model that optimizes generation dispatch as well as long-term capacity expansion decisions, to the country-specific setting of Ghana. Qualitative methods involve extensive analysis of energy policies, as well as in-person and phone interviews with Ghanaian energy planners and researchers.

Chapter 5

Model Methodology and Formulation

In the previous chapter, I reviewed existing and related work on electricity planning in SSA and Ghana specifically. In this chapter, I present the model methodology and formulation used in my analysis. I adapted the MIT EleMod model to study Ghana's power system and to explore various levels of penetration of wind and solar integration, and various levels of fuel supply and transmission constraints. MIT EleMod is a detailed bottom up capacity expansion, operations planning and dispatch model of the electric power sector that was initially designed to study the U.S. power system with large penetrations of wind. EleMod is an hourly model and so, unlike top-down or less resolved models of the power sector, it contains the required spatial and temporal resolution to capture the operational constraints that renewable resource variability introduces, particularly from wind and solar resources [84, 85].

5.1 EleMod

The MIT EleMod model is a tool for capacity expansion planning, operation planning and dispatch used to study electric power systems with penetration of renewable resources. The structure of this electricity model was inspired by the MARGEN model, a power generation expansion tool that has been used widely in the analysis of Spain's power system, and formulated to better capture challenges introduced by intermittent and variables renewable energy systems that did not exist when MARGEN was initially designed in 1987 [84, 86, 87].

EleMod is an annual recursive-dynamic model mainly targeted to understand "a) the evolution over time of the generation mix of an electricity system with increasing penetration of intermittent generation such as wind or solar photovoltaic, and b) the behavior of electricity market prices under large penetration of renewable resources" [84]. The model calculates marginal prices for the wholesale supply of energy in the short-term, guarantee of supply long-term and the operating reserve by minimizing total production costs using a rich resolution of data on hourly load and renewable energy resources to capture the effects of intermittency on the system's expansion and operating capacity [84]. This deterministic linear programming model was initially developed to analyze the effect of increased penetration of renewables across the continental U.S., yet the modular design of the model allows for application to different geographical regions [84]. EleMod considers three time ranges in the decision-making process: capacity expansion planning, operation planning and dispatch in its power generation cost-minimization formulation.

The following section reviews the mathematical formulation of the model, as originally proposed by Tapia-Ahumada and Perez-Arriaga, followed by the core data used

Table 5.1: Indexes used in EleMod

Symbol	Name
r	Region
t	Year
d	Day
h	Hour
n	Thermal-based generation technology
c	Wind class technology
sc	Solar class technology
f	Types of fuels used for generation

with a review of the data collection and preprocessing stage.

5.1.1 Model Formulation

As outlined by [84, 85], EleMod is centered around an objective function that minimizes total system's costs subject to various constraints. This section provides a breakdown of the various system constraints and the objective function of this model.

Tables 5.1, 5.3 and 5.4 list the notation for the variables used in the model formulation, the inputs required by the model and the decision variables respectively.

5.2 EleMod for Ghana

5.2.1 Data Sources, Processing and Parametrization

A substantial portion of the methodology involved data collection and pre-processing. Core data for parametrizing the model was obtained based on published figures from the Ghana Energy Commission (EC) on the operation of the power sector. Another aspect of data collection involved interviewing various stakeholders in the sector to act as the link between the theory of economic dispatch and generation expansion of power systems and the reality of developing capacity and dispatching electricity in Ghana's constrained power system. Most of the data used is published by the EC, which releases actual system performance six months to a year after a calendar year ends. For example, complete information on power system operation in 2016 was available by August 2017. 2016 is used as the baseline year in the model as more recent years do not as yet have complete data available.

5.2.2 Input Parameters

Regional Classification - Ghana has a centralized government, but as of 2016, had 10 administrative regions. The Southeast is home to Accra, the capital city, and industrial areas, such as Tema, which are major load centers. Ghana's economy is driven by its major export industries - gold, cocoa, petroleum and timber, which are located in southwest Ghana. Northern Ghana mainly consists of sparsely populated, rural populations with low energy demand.

Electricity distribution in Northern Ghana is overseen by NEDCo while ECG is in charge of distribution in the South. Based on demand characterization, I split Ghana into three regions: Region 1 in the Southeast (residential and industrial customers), Region 2 in the Southwest (industrial customers), and Region 3 in the North (residential and rural customers). **Figure 5-1** shows the regional classification of Ghana employed in EleMod.

Figure 5-1: Regional classification of Ghana in EleMod

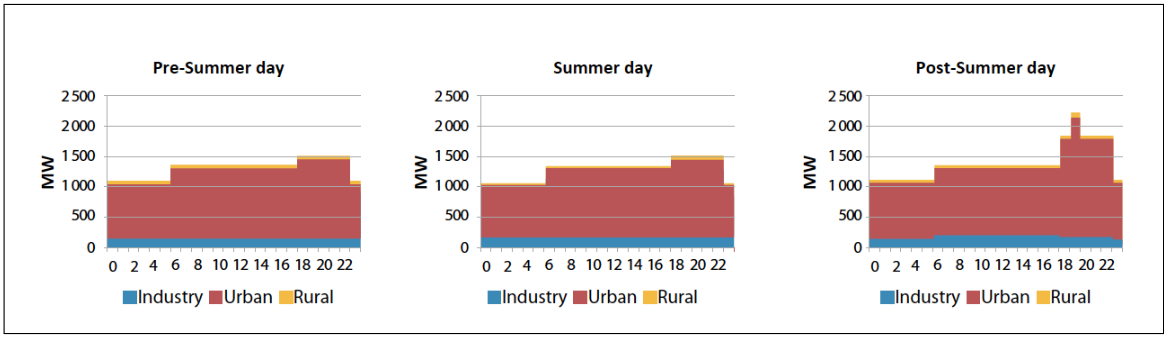


Figure 5-2: Ghana Load Shape Data for day in 2012 [13]

Demand - The hourly load profile for 2016 was defined for all three regions. First, I obtained publicly available figures on monthly energy and peak energy consumption for every substation in the country. These substations were classified under the ECG or NEDCo zones. All substations under NEDCo were classified as Region 3 customers in EleMod. By using the list of large industrial customers located in Southwest Ghana, which were mainly mining and textile companies, I then classified each substation in the ECG zone as Region 1 or Region 2 [88]. Following this, I summed up the monthly peak energy consumption for each region for 2016 assuming coincident peak demands. Then, I reached out to the authors of Diawou et al. (2017), who conducted similar analysis on generation expansion in Ghana, and they provided the total hourly energy consumption for at least one day for every month in 2014 [77]. Then, I normalized the hourly demand based on peak energy, which usually occurs between 6 and 10 pm [77].

Following this, I made two key assumptions around load profiles. First of all, I assumed that the normalized hourly profile over one day was representative of demand across the month. Secondly, I assumed that energy demand across regions differed in terms of magnitude, but did not differ significantly in the actual hourly profile. This logic was partly informed by the actual hourly profile observed in **Figure 5-2** and by the fact that I was unable to obtain a breakdown of hourly energy consumption by region. Using these assumptions, I used the hourly profile and monthly peak energy demand per region to calculate the hourly energy demand for 2016 across the three EleMod regions [5, 88].

Concerning future demand projections as required input for generation expansion decisions, demand for 2017 and 2018 was based on historical data, whereas a 5% annual increase in energy demand was assumed for the years thereafter (2019 - 2040). These projections will likely overestimate true demand. Thus, future work can explore the sensitivity of the results obtained to different levels of demand growth [88].

Technology Attributes - **Table 5.2** lists the five conventional thermal generating units types considered in this analysis. Coal and nuclear powered generating units were not included, because they are not included the government's medium-term energy outlook.

Since Ghana's total capacity in 2016 was relatively small at approximately 3.4 GW, I had to decide whether to model each power plant individually or aggregate them based on similar technology attributes. Given that it is highly unlikely that future generating units would exactly mirror the existing generation fleet, I aggregated generating units by fuel type and engine type. Based on this, I then obtained the technology and cost attributes for each of the existing generation fleet from publicly released documents and used a weighted average to calculate the attributes for the aggregated technology types [5]. Additionally, in an attempt to make the model projections more realistic, our reference case (discussed in detail in Chapter 6), specifies the expansion pathway for 2016-2024 for all thermal, solar, wind and pumped hydro

Table 5.2: Thermal Generation Technology Type

Symbol	Technology Type	Abbreviation
n01	Combined Cycle Dual Fuel	GasLCO CC
n02	Natural Gas Turbo Engine	Gas TE
n03	Combined Cycle Diesel and Light Crude Oil Plant	DFOLCO CC
n04	Combined Cycle Residual Fuel Oil Turbine	RFO CC
n05	Simple cycle diesel power plant	DFO SC

storage technologies based on projects currently nearing completion or in late-stage development [5].

Technology attributes for wind and solar were obtained from [5], which provided current and future cost estimates for both resources. To account for the increased cost of doing business in Ghana [1], I assumed an interest rate of 14% when calculating the total overnight costs [89]. This rate is a reasonable rate used by private investors when developing higher risk projects in African countries [11].

Wind and Solar Resources - Ghana has sizable wind and solar resources across all regions, which opens up the possibility of a significant contribution of renewables to power generation [5]. Hourly solar profiles per region for 2000-2002 were obtained from the Solar and Wind Energy Resource Assessment (SWERA) by the National Renewable Energy Laboratory (NREL). Data provided was based on solar irradiation readings at 17 locations, which I classified under the three EleMod regions [90, 91] However, a comprehensive assessment on Ghana's total solar resource potential was unavailable, so I did not impose a limit on available solar resource.

[1] This can be measured using metrics such as the Moody's bond credit rating. Ghana current ranking stands at B3 indicating a market with high credit risk

Wind resources are typically classified in four wind classes[2], which represent the quality of a wind resource in a given location. For wind generating units, based on a generic generation profile provided by government energy planners, I generated a normalized hourly wind generation profile for each wind class [5, 90]. Given the generic nature of the data, and in order to obtain some variability in wind generation per class, I shifted each hourly wind profile by 5 hours. For example, the wind profile of class4 wind in hour 1 was equal to the wind profile of class3 in hour 5. The lack of a comprehensive spatial and temporal wind dataset is a key limitation to the model. Total available wind resource per EleMod region was generated using wind resource maps of Ghana developed by NREL [90]. The analysis provides detailed high-resolution ($1km^2$) wind power density readings across Ghana classified under the four wind classes. NREL's assessment estimated total utility-scale wind resource potential at 5.6 GW, with almost 5 GW of this resource in the moderate and good wind resource categories (wind classes 3 and 4 respectively) [90].

Hydro generation - Storage hydropower plays a significant role in Ghana's power generation, with two plants located in Region 1 and a third located in Region 3. It acts as baseload generation and, despite concerns around low hydro inflows, it often generates at close to its maximum capacity to fill the gap caused by low thermal generation due to unreliable fuel supply [5, 42]. In this model, potential hydrogeneration is classified under dry, moderate and wet scenarios. I used data on historical hydro generation to classify the generation in each calendar year from 2005-2017 under one of these scenarios. I then used the monthly hydro generation reported in publicly available data to obtain an averaged monthly profile for each scenario [88]. Finally,

[2] Wind is classified into class3, class4, class5, and class6 wind based on increasing wind speed and generation profile

under the assumption that hourly hydro generation remains fairly flat, I calculate hourly hydro profile across Regions 1 and 3 for each scenario and scale hourly hydro generation to match the typical load profile observed in both regions.

One limitation of this approach is the possibility of slightly unbalanced wet and moderate hydro scenarios. In my analysis, I classified 2005, 2006, 2015-2017 as dry hydro years, 2003, 2004, 2007, and 2013-2014 as moderate hydro years, and 2008-2012 as wet hydro years. However, since hydrogeneration has steadily declined since 2005 due to increasing thermal generation, the wet scenario might overestimate hydrogeneration. For this reason, and because recent years have seen mostly dry hydro scenarios, my analysis used the dry hydro scenario. Future work could look into the impact of hydro uncertainty on system reliability, resilience and generation expansion pathways.

Reserve and Total Reserve Margin - To ensure that reliability requirements are met, the EC recommends reserves between 20-25%, but it does not specify how much of this margin must be used for short-term energy needs that occur during unit commitment. The total system reserve margin assumed in this thesis is 10%, lower than the recommended 25%, but much closer to historical performance[5, 88]. Operating reserves was assumed to cover 1% of demand and the outage of a thermal unit with a size of 300MW.

Cost of Non-Served Energy - This cost provides an upper limit to the marginal cost of electricity. Once this limit is reached, the model will produce non-served energy rather than build new units to meet demand. Previous reports, around a decade old, put this value between $8-14 per megawatt hour (MWh) [5]. Given the strong intent of energy planners to avoid non-served energy as much as possible, a relatively high cost of non-served energy of $1400 per MWh was assumed in this thesis.

Generator Constraints

The generator stack in most power systems usually consists of many generation technology types with different technical capabilities, constraints, and costs. These include minimum plant loading, availability factor, forced outage rate, economic life time and start up and shut down costs, and these technology attributes define the operating capabilities of each generation technology [3].

Generating units typically fall under three main types with regard to operating flexibility, up and down times, and minimum operating types - baseload generators, intermediate generators and peaking plants. Units with long ramp times (defined as longer than 10 hour ramp up and down times) are usually baseload generation, with the most flexible (and expensive plants) usually comprising the peaking plants [3].

In the EleMod model for Ghana, four types of generators - based on fuel source - are considered. They are: 1) conventional thermal generating units, 2) wind units, 3) solar units, and 4) hydro generating units. Of the four, hydropower in our case and old gas and oil power plants are typically baseload generation, with more flexible thermal units used as intermediate plants, and oil and pumped hydro storage (PHS) used as peaking plants. Wind and solar power plants are classified as variable and intermittent energy resources and we allow curtailment of these resources so they do not have priority of dispatch. Additionally, since the wind and sun provide renewable generation and they have zero marginal generation costs, these power plants are usually the cheapest ones [3].

Operator-induced curtailment can however occur at higher penetration levels of renewables due to transmission congestion or lack of transmission access, excess generation during periods of low load and oversupply, and generation mismatch [3, 92]. More flexible power plants are then required to deal with the variability of solar and wind. The constant ramping up and down of these plants for increasing amounts of time can increase the wear and tear of the units and also increase the system's costs [3, 92]. Additionally, all generation, including wind and solar, might be constrained by transmission capacity, which is a measure of how much energy can be transported between the various nodes in the electric network. To manage these transmission and operational constraints, wind and solar are typically curtailed, that is, their power generation is reduced below their maximum production levels [3, 92]. This kind of curtailment is now very common in regions with high penetrations of wind and solar, especially during seasons of low load and oversupply, generation mismatch and lack of transmission capacity [3, 84, 92].

Operating Constraints

Maximum and minimum generation - When making economic dispatch decisions, the units are constrained by their upper and lower generation limits. Units cannot generate power above their maximum rated size, and they also have a minimum generation level they operate at.

Spinning Reserve - Spinning reserves are usually on-hand during unit commitment decisions to ensure that short-term reliability requirements are met in the event of sudden loss of generation. Ghana's power system planning documents fail to spec-

Table 5.3: Inputs required in EleMod

Symbol	Name
$c^{fix}_{r,n}$	Annualized fixed cost for technology n, in region r
$cw^{fix}_{r,c}$	Annualized fixed cost for wind class c, in region r
$cs^{fix}_{r,sc}$	Annualized fixed cost for solar class sc, in region r
c_PHS	Annualized fixed cost for a PHS unit
$p^{fuel}_{r,n}$	Fuel price for technology n, in region r
$hr_{r,n}$	Heat rate for technology n, in region r
$c^{vom}_{r,n}$	Variable operating and maintenance cost for technology n, in region r
p^{CO2}_{r}	Price for CO_2 emissions in region r
$Cap^{CO2}_{t,r}$	CO_2 emissions limit in region r, for year t
$ef^{CO2}_{r,n}$	CO_2emission factor for technology n, in region r
c^{nse}	Penalization for non-served energy
$d_{t,h,r}$	Demand for year t, hour h, in region r
$k^0_{r,n}$	Installed capacity of existing thermal-based conventional generators per technology n, in region r
$kw^0_{r,c}$	Installed capacity of existing wind per class c, in region r
$ks^0_{r,sc}$	Installed capacity of existing solar per class sc, in region r
$kh^0_{r,sc}$	Installed capacity of existing hydro in region r
$kphs^0_r$	Installed capacity of existing pumped hydro storage in region r
$esize_PHS$	Energy Storage for a PHS unit in hours
$psize_PHS$	Capacity limit for a PHS unit per region r
$rw^0_{r,c}$	Wind resource in region r, per class c
$\omega^0_{r,c}$	Wind generation profile in region r, per class c
$s^0_{r,sc}$	Solar generation profile in region r, per class sc
lt_n	Economic lifetime of thermal-based generation conventional technology n
ltw_c	Economic lifetime of wind technology n, per class c
lts_{sc}	Economic lifetime of solar technology n, per class sc
$f^{forced}_{r,n}$	Forced outage rate for conventional technology n, in region r
$f^{firm}_{r,c}$	Firm capacity of wind technology c, in region r
$f^{firm}_{r,sc}$	Firm capacity of solar technology sc, in region r
$m^{reserve}_r$	Capacity margin reserves for long-term reliability in region r
$l^{min}_{r,n}$	Minimum load for conventional generators in region r, per technology n
$Cap^f_{r,n,f}$	Fuel consumption for conventional technology n, in region r

Table 5.4: Decision variables in EleMod

Symbol	Name
$vK_{t,r,n}$	Installed capacity in year t, per region r and conventional technology n
$vKw_{t,r,c}$	Installed wind capacity in year t, per region r and wind class c
$vKs_{t,r,sc}$	Installed solar capacity in year t, per region r and solar class sc
$vKphs_{t,r}$	Installed pumped hydro storage capacity in year t, per region r
$vG_{t,h,r,n}$	Generated power in year t, per hour h, per region r and conventional technology n
$vGw_{t,h,r,c}$	Generated wind power in year t, per hour h, per region r and wind class c
$vGs_{t,h,r,sc}$	Generated solar power in year t, per hour h, per region r and solar class sc
$vGwCur_{t,h,r,c}$	Wind curtailment in year t, per hour h, per region r and wind class c
$vGsCur_{t,h,r,sc}$	Solar curtailment in year t, per hour h, per region r and solar class sc
$vCP_{t,j,r,n}$	Connected power in year t, per day j, per region r and conventional technology n
$vSU_{t,j,r,n}$	Connected power started up from day (j-1) to day j
$vSD_{t,j,r,n}$	Connected power shut down from day (j-1) to day j
$vNSE_{t,j,r,n}$	Non-served energy in year t, per hour h, per region r
$vFU_{t,r,n,f}$	Fuel use in year t, per fuel f and conventional technology n, in region r
$vOPD_{t,h,r}$	Shortage in downward reserve in year t, per hour h, per region r
$vOPU_{t,h,r}$	Shortage in upward reserve in year t, per hour h, per region r

ify an exact requirement [5].

Net demand - In each period, net electricity generated must always equal net demand.

Start-up and shut-down constraints - In each period, the start-up and shut-down power from day j-1 to day j must equal the change in the connected power per technology over the same period.

Fuel Switching - Ghana's power generation system has consistently faced fuel supply shortages, mainly natural gas shortages that affect the operation of the majority of its generating fleet [5]. As such, most of its thermal power plants are dual-fuel power plants that can usually run on both natural gas and oil [88, 93]. Given the non-trivial occurrence of fuel switching, usually from natural gas to crude oil, we included a constraint that caps the annual fuel consumption per technology type. Once the fuel cap is reached, generation for the given conventional technology ceases and the system uses other generating units such as solar and wind, or producers non-served energy (NSE).

$$vG_{t,h,r,n} = \sum_{fuel} vGfuel_{t,h,r,n,fuel} \tag{5.1}$$

$$vGtot_{t,h,r,n} = \sum_{t,h,n} vGfuel_{t,h,r,n,fuel} \tag{5.2}$$

$$vFuelUse_{t,h,r,n,fuel} = vGfuel_{t,h,r,n,fuel} * hr_{n,fuel} * 10^6 \tag{5.3}$$

$$vFuelUseyr_{t,r,n,fuel} = \sum_h vFuelUse_{t,h,r,n,fuel} \tag{5.4}$$

$$vFuelUseyr_{t,r,n,fuel} < \sum_h fuelcap_{r,n,fuel} \tag{5.5}$$

Restrictions on wind and solar capacity and energy production - Wind and solar energy production must not exceed the available resource capacity of each technology.

Pumped Hydro Storage - Pumped hydro storage (PHS) is modeled as a flexible storage technology that charges and discharges energy. Its maximum energy storage is based on its total storage capacity of 8 hours and its minimum energy storage of at least 1 hour. Additionally, capacity additions of PHS are limited by the capacity limit per region.

Long-term reliability requirement on installed capacity - This constraint requires a certain percentage of overbuild in the system's total installed capacity, which we defined as a 10% reliability margin.

CO2 emissions constraint -This constraint imposes a constraint on total CO_2 produced by thermal generating units, which allows for exploration of the role of possible energy and environmental policies on the generation mix.

Objective Function - This model optimizes dispatch decisions and capacity expansion subject to the system's operation constraints to minimize total system costs.

$$MinTC(r) = C_{Annualized} + C_{Operational} + C_{Startup} + C_{Shutdown} + C_{Non-ServedEnergy} \tag{5.6}$$

5.2.3 Solving the Model

The model is formulated in the General Algebraic Modeling System (GAMS) modeling language as a recursive-dynamic linear programming model that solves the mixed integer program (MIP) [84, 85]. For this study, EleMod optimizes generation expansion by minimizing total systems costs under various scenarios. A sequential optimization is used for a time period ranging from 2016 to 2040, based on a two-year time steps [84, 85]. By comparing metrics such as total system's costs, installed capacity, absolute generation per technology type, and carbon emissions, I assess various generation pathways in Ghana's power system.

5.2.4 Key Model Assumptions and Limitations

Like any model, EleMod for Ghana includes important assumptions and has some limitations that are listed below.

Model Assumptions are:

- New installed capacity
    - New plants come online at the beginning of a year.

- Installed capacity linearly depreciates based on economic life.
- Power plants announced that come online during odd-numbered years are built a year later (e.g. Plant A scheduled to come online in 2021 is assumed to come online in 2022 to account for usual construction delays and typical delay observed for projects).
- Nuclear and coal technologies are not considered relevant for the analysis done in the thesis.

• Load Dispatch

- Load is dispatched according to the order of merit curve, that is, the cheapest energy resources are dispatched first. However, this economic dispatch is adjusted to account for additional costs such as start-up costs, and minimum technical load conditions.
- Solar and Wind are assumed to have no variable costs and tend to be dispatched first but they can be curtailed in the case of oversupply, transmission constraints, minimum loading constraints and other operation constraints. Additionally, solar and wind costs decline annually by 2% and 1% respectively
- Non-served energy is represented through the value of lost load (assumed to be $1400 per MWh).
- The typical load profile across consumer classes and regions remains similar to the 2015 load profile data.

Key model limitations are:

- Hydropower is input as a fixed value, which does not allow for taking advantage of its storage capabilities and flexibility especially in the integration of renewables and it role in providing ancillary reserves.

- The annual hourly wind generation profile is not reliable and a more comprehensive spatial-temporal dataset is needed.

In the next chapter, I introduce the scenarios considered in my analysis.

Chapter 6

Results and Discussion

In the previous chapter, I outlined the model methodology. In this chapter, I describe the scenarios explored and present the results with a specific focus on the impact on Ghana's power system reliability.

6.1 Scenarios

Each year, the EC releases an electricity supply plan for the country with an outlook about the state of power supply in the short and medium-term. This report is produced in collaboration with the grid operator, government and quasi-governmental power producers, and the distribution companies, and includes official announcements of planned power plants [42]. Using these official reports, I obtained a list of power plants that are due to come online up until 2024, including their various technology attributes, and I defined fixed capacity additions for thermal generation and upper limits on wind and solar capacity expansion for that time window. All scenarios include these capacity restrictions through 2024 to reflect the actual plans in Ghana. All scenarios also assume:

- A cost of non-served energy of $1400/MWh
- Fuel price projections for 2016-2040 from the World Bank and Ghanaian government projections
- Mid-level firm transmission capacity between all three regions based on current and near-term plans for firm transmission capacity
- Upper limits on wind and solar expansion from 2016-2040
- A dry hydropower scenario.

The reference case (REF), which is the business-as-usual scenario, assumes: (1) a limit on the expansion of wind and solar capacity to 2.8 GW and 5 GW per modeling period, respectively, (2) a flat fuel cap based on the fuel consumption in 2016, and (3) no new storage technologies, specifically pumped hydro storage (PHS), exist in the system. Additional scenarios explore how increased renewables, fuel supply shortages and a flexible generation option (PHS), impact generation expansion and operation.

An important question relates to the potential value of renewables to Ghana's power generation system. The limits on the expansion of renewables in the REF case are imposed to obtain generation pathways that are technically feasible given the current state of the renewable energy industry in Ghana and grid stability concerns under high penetration of renewables. However, if grid integration and challenges related to the speed of capacity expansion were somehow resolved, renewables would play a larger role. To explore this, I include a scenario that removes the upper limit imposed on wind and solar expansion (REF2). The outcome of this scenario is expected to inform how integration could be done in the future as well as the economic support required to allow this type of deployment in Ghana's system.

Since fuel supply issues were a main cause of the power crisis in Ghana, a key question is how fuel shortages affect the system's reliability. I explore this by comparing the reference case, which has a fuel cap, with a scenario with no cap on the amount of fuel that can be used by the power sector (NOCAP). If fuel supply problems are resolved, and Ghana has no constraints on the amount of fuel used, does system reliability improve?

Another key question is how flexible generation options like PHS, combined with renewable generation, could improve the reliability of Ghana's power system. Ghana initially had a 10% RPS by 2020 target, which has now been pushed to 2030. One key limiting factor for increased grid integration of variable renewable energy technologies (RETs), such as solar PV and wind, is the impact of their intermittency on the national grid. GRIDCo and ECG have been evaluating the impacts of large utility-scale solar PV grid integration. The IRRP Workshop held in October 2017 in Accra noted that the system's current conditions cannot accommodate variable and intermittent renewable energy capacity beyond 10–15% of the total grid capacity [5]. Flexible technologies such as PHS have the potential to increase the system's ability to accommodate RETs. To explore this, I include scenarios, both with and without a fuel cap, that include PHS as an available technology option (REF+PHS, REF2+PHS and NOCAP+PHS).

The six scenarios are summarized in **Table 6.1**. Each case is run in two-year time

Table 6.1: Summary of Scenarios

Scenario Name	**Scenario Description**
REF	Reference case with a cap on the amount of fuel used in the power sector (fuel use is limited to 2016 levels), limits on wind and solar expansion and no pumped hydro storage available
REF2	Same as reference case with no limits on wind and solar expansion
NOCAP	Same as the reference case, but with no cap on the amount fuel used in the power sector
REF+PHS	Same as the reference case, but with pumped hydro storage available
REF2+PHS	Same as REF2, but with pumped hydro storage available
NOCAP+PHS	Same as NOCAP, but with pumped hydro storage available

steps from 2016 to 2040 to determine the capacity expansion decisions, and in 30-hour time-steps for each of those years to determine the optimal operation. Given the focus on reliability in this analysis, the metrics highlighted are the level of non-served energy and spinning reserve shortages, and their impacts on changes in total system costs.

6.2 Generation Operation and Expansion

6.2.1 Benchmark Year: 2016

In 2016, the first year analyzed, the system is composed of thermal generation and hydropower with negligible solar and no wind generation.

Model validation, as shown in **Table 6.2**, reveals that EleMod results are strongly

Table 6.2: Model Validation for 2016 Operations

Metric (in GWh)	**EleMod Results**	**Actual System Performance**
Thermal Generation	5,940	7,381
Hydrogeneration	5,572	5,560
Non-Served Energy	664	Data not available
Imports	-	745
Solar Generation	21	30
Ghana System Total	12,198	13,693
Proportion of Thermal Generation (%)	**49**	**54**

comparable to the actual reported system's performance, with thermal generation slightly underestimated by the model. This is likely due to differences in actual vs. modeled system requirements of long-term reserves, total system demand and the value of lost load. First, official planning documents for 2016 stated that, "The Ghana power system will have low reserve margin in 2016 and therefore when units are out for maintenance the system will be prone to inadequate supply" and projected the long-term reserve margin would lie between 17% and 3% [94]. However, cases in our study impose a fixed reserve margin of 10% across all model runs. Secondly, EleMod does not model electricity exports and imports or system losses. In reality, electricity losses and imports totaled 607 GWh and 745 GWh in 2016, respectively [88]. Finally, the non-served energy value of $1400 per MWh used in EleMod might deviate significantly from the actual value, which would overestimate or underestimate NSE, depending on whether the price is too low or too high. The system operator does not report total NSE nor its cost.

6.2.2 Reference Scenarios

Figure 6-1 shows the installed capacity and generation expansion pathways until 2040 for the REF and REF2 cases.

Of note in both scenarios is the generation expansion pathway from 2016-2024, the period during which I defined installed capacity based on Ghana's medium-term energy outlook. During this period, Ghana's power system has a generation mix heavily dominated by thermal generation, as well as a sizable amount of non-served energy (NSE). In the REF2 case, once the model is allowed to build generation beyond 2024 without restrictions, we see an immediate build-out of significant amounts of renewables, especially wind, which results in no more NSE in the system. In the REF case, imposing restrictions on wind and solar expansion still results in significant build out of renewables, especially solar. However, the restrictions imposed on both fuel consumption and renewable energy expansion result in significant amounts of NSE in the system. Also of note is that the fuel cap is binding gas and oil generation in all years, with both generating at the maximum level allowed given the constraint on fuel. Under REF2, the fuel cap is binding in some years, but not all.

In the REF2 case, by the end of the planning period in 2040, wind forms 54% of the total generation mix. The wind generation profile used in the model strongly correlates with the system's load profile and, unlike solar, wind generation occurs during all hours of the day, especially during the system's peak demand period in the evening. **Figure 6-2** shows hourly wind and solar generation and system demand in Region 1 for a single day (January 1st 2026) to highlight how the profiles of both resources compare with Ghana's typical daily load profile. As we see, Ghana's peak demand occurs between 6 and 10 pm, and sunset in Ghana usually occurs by 6 pm year-round. Due to this mismatch, solar provides a much less important contribution to the energy mix than wind. The other regions show the same patterns. It is also important to note that because hydropower modeling in EleMod is limited, and since hydropower is an important flexible technology, the penetration of renewables may be underestimated.

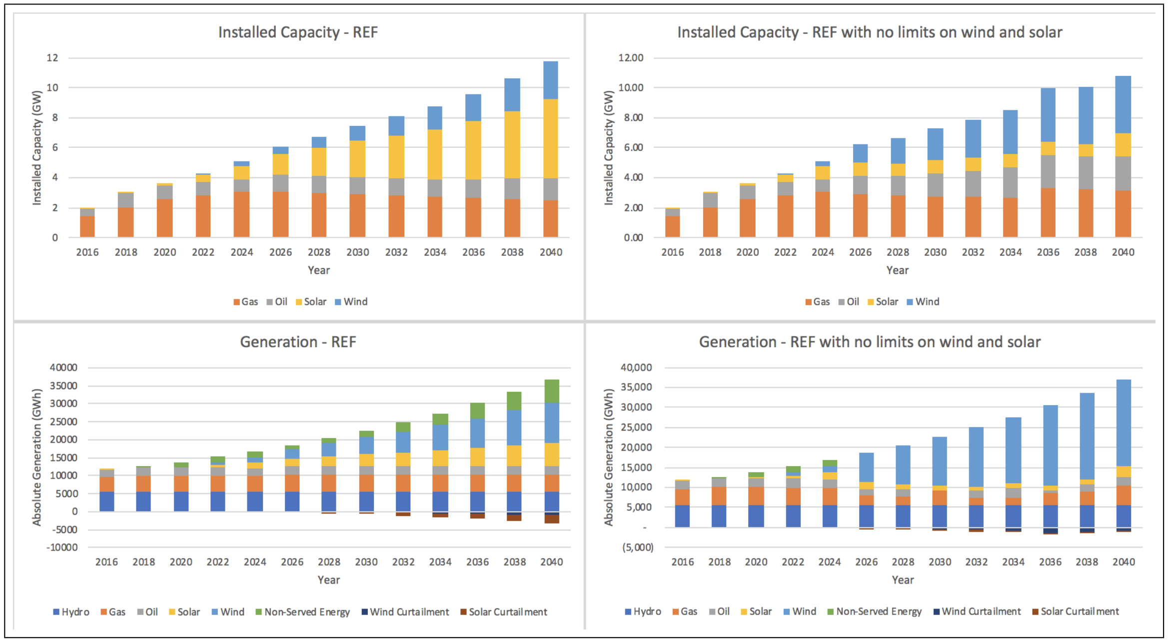


Figure 6-1: Generation Expansion Capacity in GW (top) and Annual Generation per technology in GWh for 2016-2040 for REF case (left) and REF2 case (right)

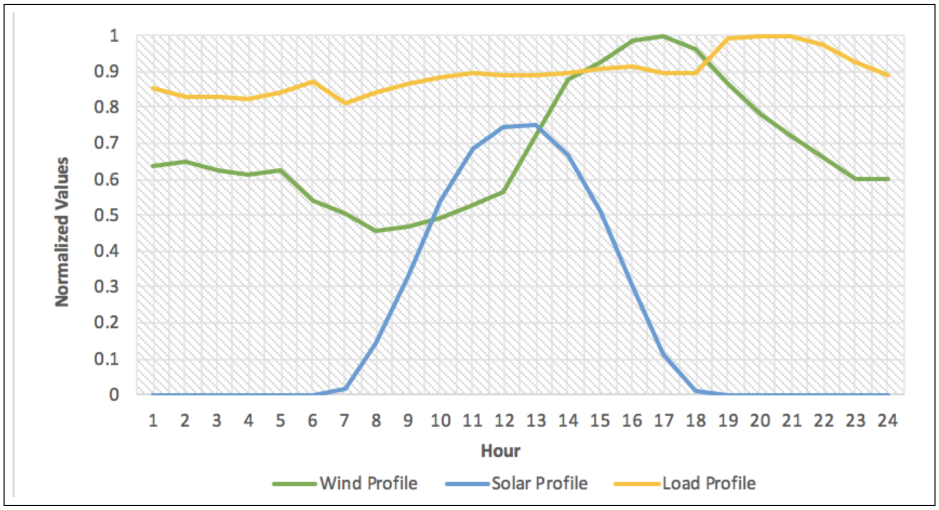


Figure 6-2: Region 1 Renewable Energy and Load Mismatch for Jan 1 2026

Figure 6-3 shows the generation profile for the first week in 2026 across all three regions under the REF2 case in order to highlight the contribution of renewables. 2026 is the first year without assigned capacity levels, so the model is optimizing generation expansion, and that leads to no NSE. This generation profile also shows that Region 1, which is located in Southeast Ghana and is home to major load centers, has the most diverse generation mix. Baseload generation comes mainly from hydropower and is supplemented by thermal generating units, mostly gas-fired combined cycle power plants, as well as renewables, which supply energy throughout the day. The figure also shows that Region 2 has a generation mix dominated by thermal generation, with slight contributions from wind. The region is home to large gas-fired combined cycle power plants with low forced-outage rates, and relatively low fixed and variable costs. As such, thermal gas generation is consistently used right up to the level imposed by the fuel cap. Wind's lower contribution is because the year is 2026 and the system has not had time to build. Finally, Region 3 has the lowest demand across all three regions. Its generation mix features no thermal generation, but rather is comprised of baseload hydropower from the Bui hydro dam, and a mix of wind and solar. The variability of the solar resource is clearly observed in this region, whereas wind generation provides a more dependable source of energy to meet the system's demand needs.

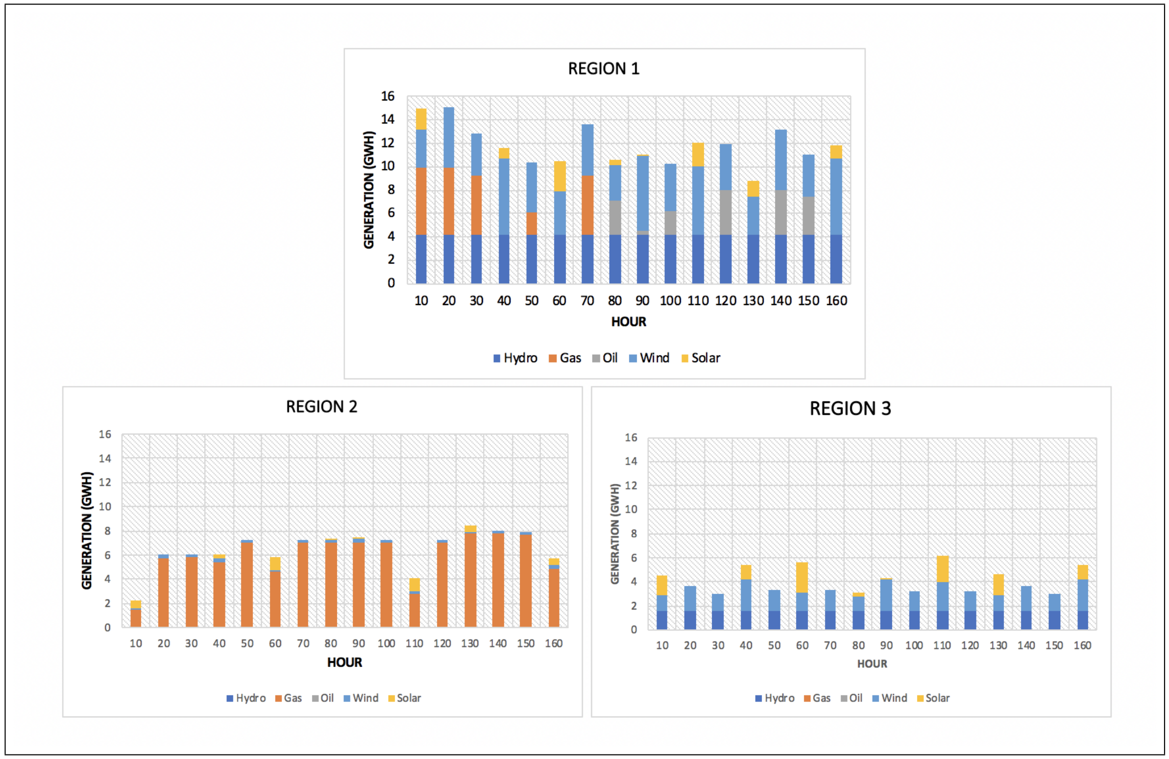


Figure 6-3: REF2 case generation profile for one week in 2026

6.2.3 Additional Scenarios

To study the role of pumped hydro storage and renewables and explore the impact of security of supply on Ghana's generation expansion, I considered four additional scenarios: REF+PHS, REF2+PHS, NOCAP and NOCAP+PHS. By running the REF+PHS, REF2+PHS and NOCAP+PHS scenarios, I explore whether the inclusion of PHS would reduce NSE especially between 2016 and 2024. It is expected that PHS would reduce or completely eliminate non-served energy in the system, thus improving electricity reliability and reducing the associated costs of non-served energy and spinning reserve shortages. The no fuel cap scenarios (NOCAP and NOCAP+PHS), which remove restrictions on fuel supply, help explore the evolution of fossil fuel dependency in the system. It is expected that there would be higher fuel consumption in the scenarios without a fuel cap, which would lead to a comparably higher proportion of thermal generation in the mix.

Generation Mix

Figures 6-4, 6-7, 6-8 and 6-9 show the generation expansion pathways until 2040 under each of the cases. To highlight the differences in the generation mix between these four scenarios, the remaining figures in this section focus on three years: 2024 (the last year of the Government Planning Outlook), 2032 (midway through the planning period), and 2040 (the last year of the planning period).

Comparing the REF2 and REF2+PHS cases shows that without a limit on solar and wind expansion, PHS leads to an overall increase in renewables in the generation mix, particularly solar, and reduces fossil fuel dependence, particularly oil. By 2040, solar plays a larger role and wind generation steadily increases from 2024 to 2040 to become the dominant generation technology (see **Figures 6-4**). Solar generation

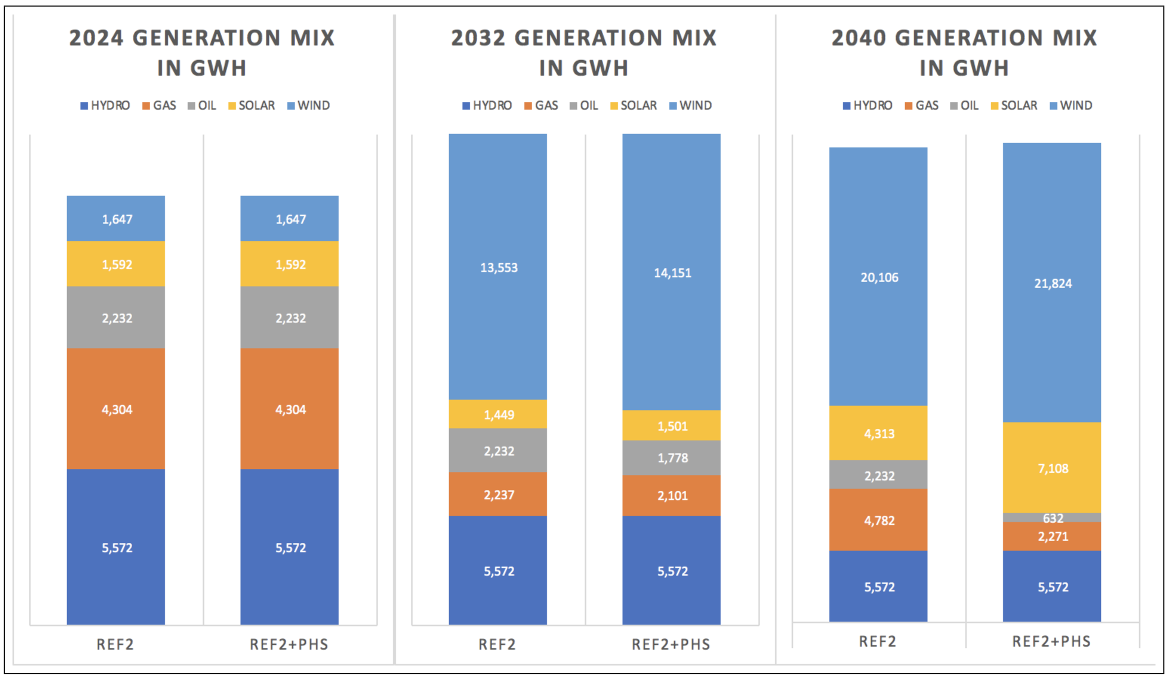
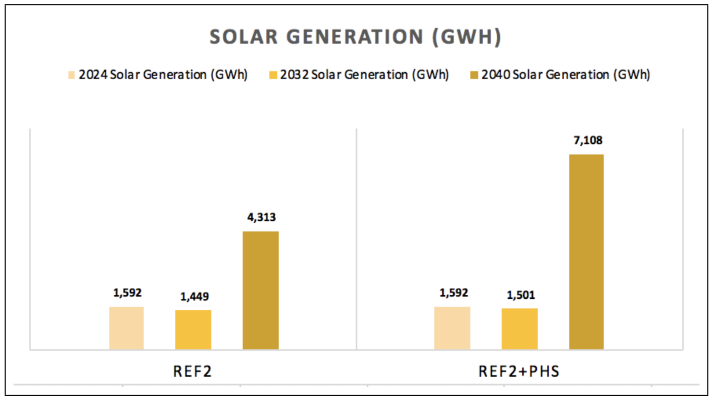
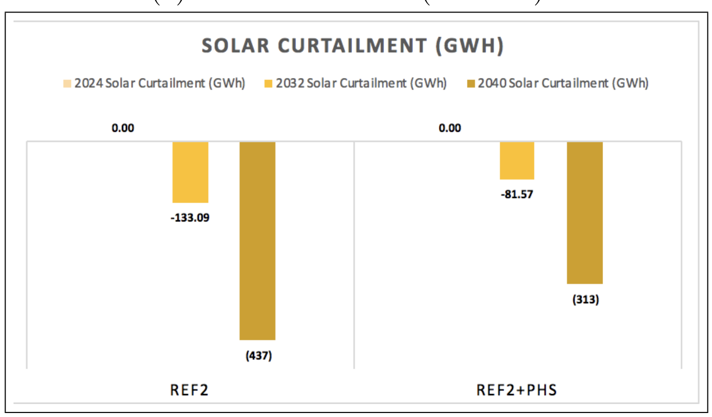


Figure 6-4: REF2 and REF2+PHS cases: 2024-2040 Electricity Generation Mix (in GWh)

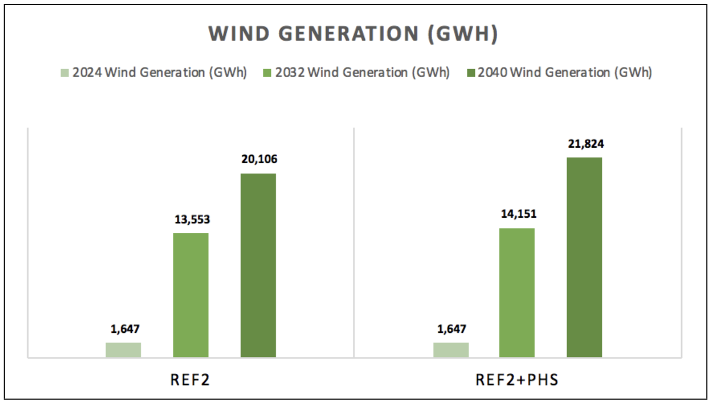


(a) Solar Generation (in GWh)

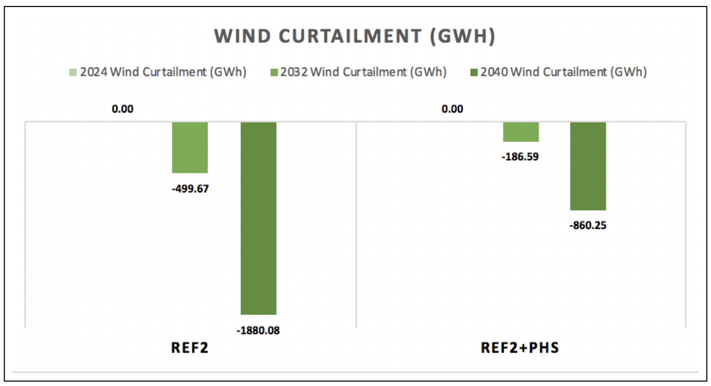


(b) Solar Curtailment (in GWh)

Figure 6-5: REF2 and REF2+PHS cases: Solar Generation (a) and Curtailment (b) (in GWh)



(a) Wind Generation (in GWh)



(b) Wind Curtailment (in GWh)

Figure 6-6: REF2 and REF2+PHS cases: Wind Generation (a) and Curtailment (b) (in GWh) starts at 23 GWh in 2016 and grows to 7,108 GWh in 2040 in REF2+PHS, compared to 4,313 GWh in 2040 in REF2. Adding PHS also decreases both solar and wind curtailment over the planning period (see **Figures 6-5 and 6-6**).

The REF2 and REF2+PHS cases were modeled to highlight the potential value of renewables to Ghana's power generation system. To ground my analysis in what is technically feasible given Ghana's current grid infrastructure, the rest of this analysis will focus on four of the six scenarios - REF, NOCAP, REF+PHS and NOCAP+PHS. I first focus on generation, and then explore non-served demand and curtailment of renewables.

In the year 2024, as **Figure 6-7** shows, the generation mix remains the same across the REF and REF+PHS, but under the scenarios without fuel restrictions thermal generation increases and displaces solar generation. Although there is the same amount of thermal installed capacity in all cases, in the cases with no fuel cap, since the thermal generating units are not limited by fuel supply they have higher capacity factors. As a result, the system has higher total generation in the no fuel cap cases as NSE has been eliminated.

By 2032, wind generation forms 24-26% of the generation mix across all four scenarios (see **Figure 6-8**). Wind generation remains high across all these scenarios due to the strong correlation between the wind generation profile and load profiles across all three regions, which might not be as strong if more comprehensive data was available. Yet solar, which forms 18% of the generation mix in the fuel cap scenarios, is completely displaced by thermal generation in the no fuel cap scenarios. Adding PHS to a system with no fuel cap increases the contribution from oil generating units, which are largely located in Region 1.

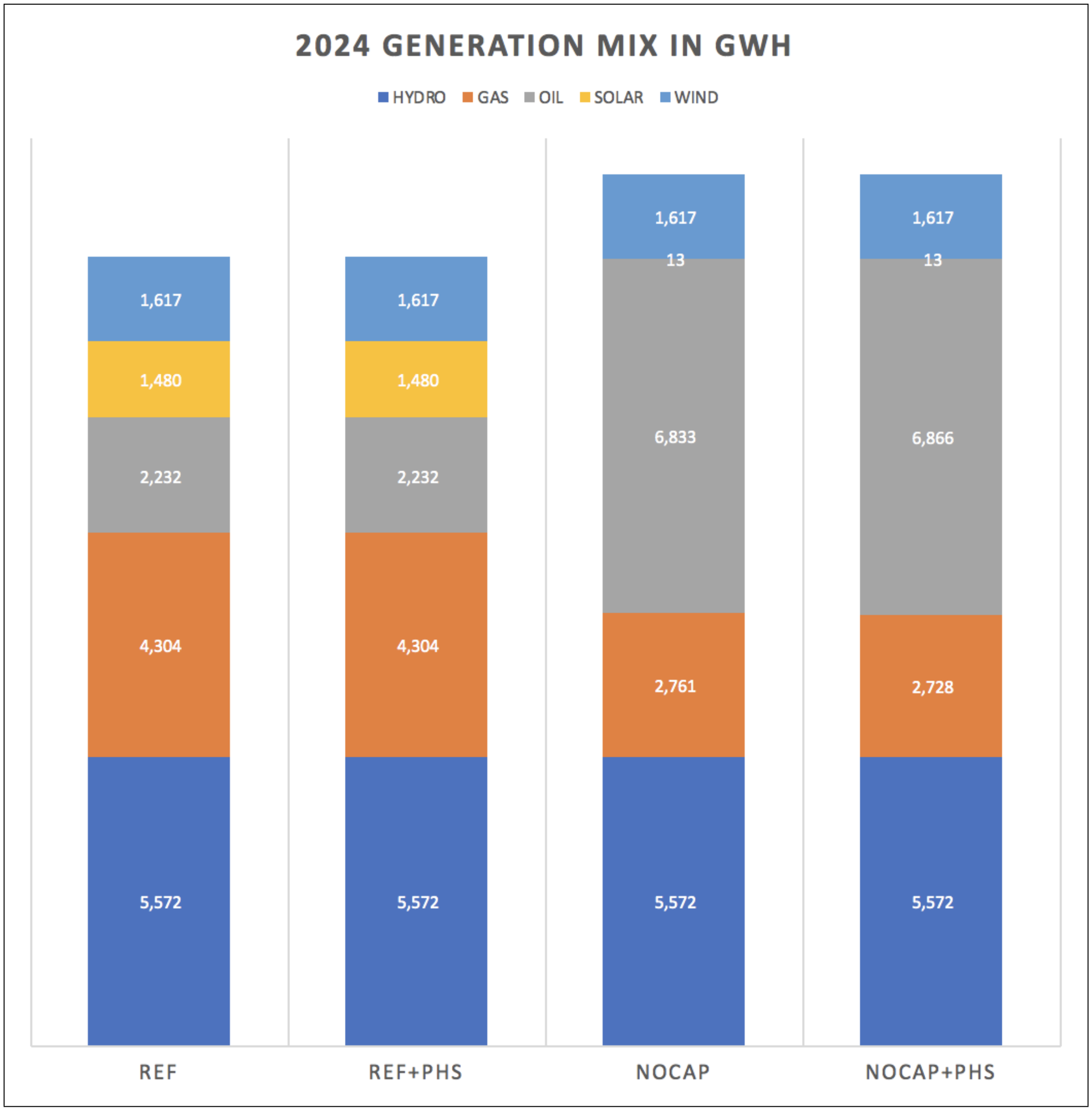


Figure 6-7: 2024 Electricity Generation Mix (in GWh)

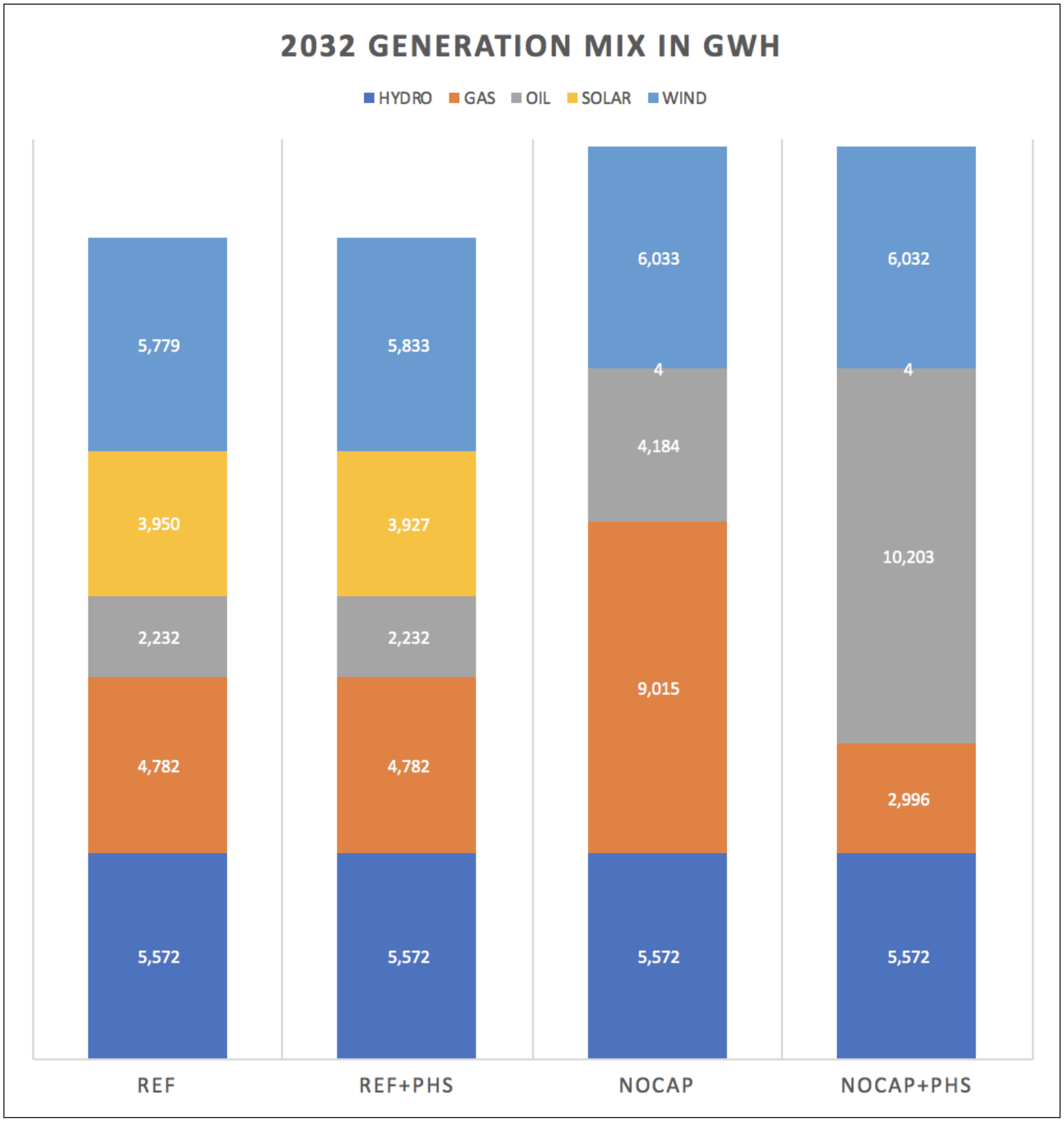


Figure 6-8: 2032 Electricity Generation Mix (in GWh)

By 2040, solar plays a larger role (see **Figure 6-9**). Comparing the REF and REF+PHS cases shows that PHS has a negligible impact on the penetration of renewables. This is largely due to the restrictions on wind and solar expansion imposed in the model. As such, thermal generating units operate at the highest capacity allowed by the fuel cap. PHS similarly has little observable impact between the NOCAP and NOCAP+PHS cases as well due to the large contribution of thermal generation. However, PHS does eliminate spinning reserve shortages in the system in both the reference and no fuel cap cases.

There are some trends that appear in these four scenarios. First, as shown in **Figure 6-10**, natural gas generation increases between 2032 and 2040 in all cases except the NOCAP case. However, natural gas expansion differs by region. In Region 1, from 2032 to 2040, combined cycle gas decreases from 5,392 to 1,215 GWh in the NOCAP case, and increases from 637 to 1,147 GWh in the NOCAP+PHS case. In NOCAP+PHS, this gas generation is supplemented by dual-fuel diesel and crude oil power plants, which grow from 2,293 to 5,372 GWh in Region 1 during the same period. In contrast, in Region 2, combined cycle gas generation increases in both cases with a larger change in the NOCAP case (from 638 to 1,147 GWh from 2032 to 2040) than under the NOCAP+PHS cas (from 2,333 to 2,590 GWh). In Region 3, there is minimal thermal generation capacity across all the scenarios. Additionally, across all four scenarios, on average, generation from diesel power plants and gas engine turbine power plants become negligible because either PHS increases the penetration of renewables or other thermal generators like combined cycle gas plants have cheaper operating costs. Diesel and gas engine turbine power plants typically represent expensive back-up generators that operate as emergency and/or peaking power plants.

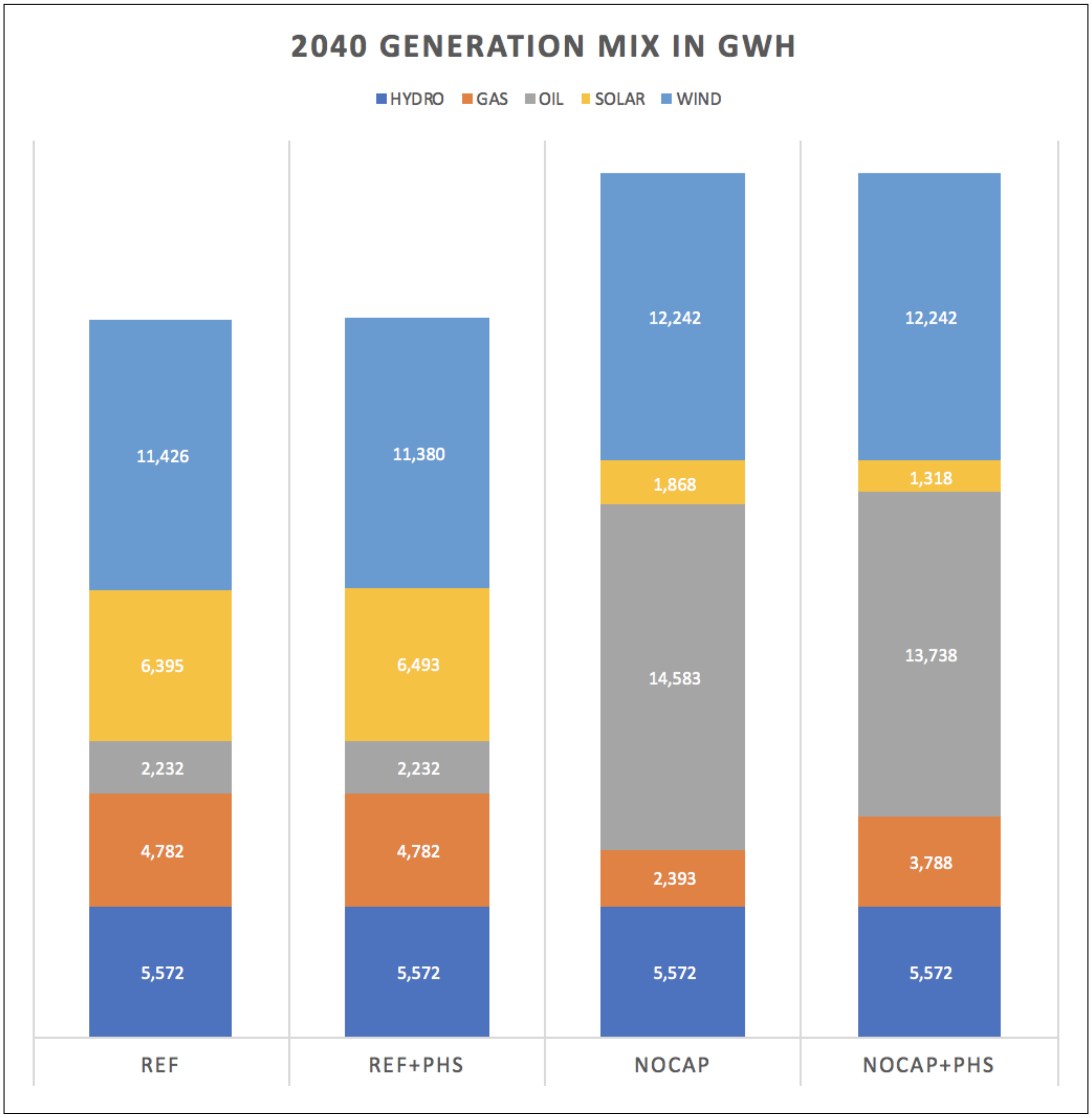


Figure 6-9: 2040 Electricity Generation Mix (in GWh)

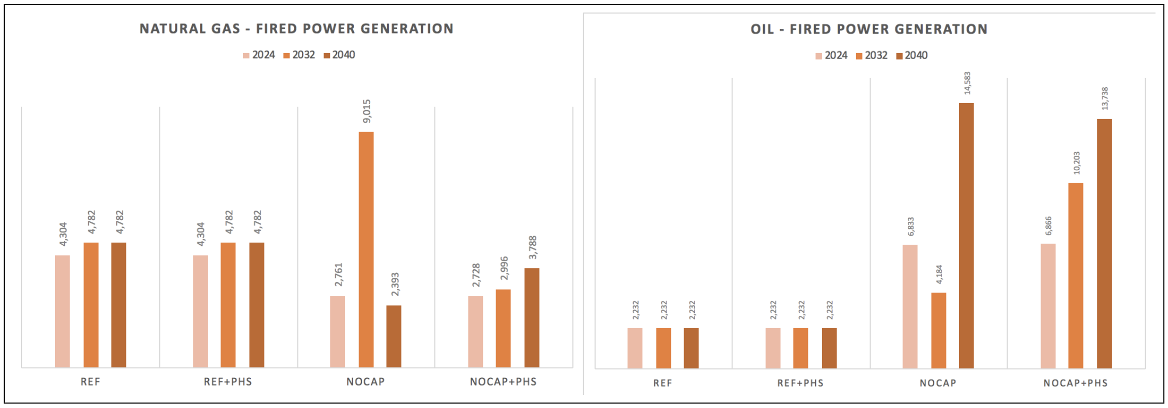


Figure 6-10: Thermal Generation

Second, in all cases, wind generation steadily increases from 2024 to 2040 to become the dominant generation technology in the fuel cap scenarios and on equal standing with thermal generation in the no fuel cap scenarios. This is due to its energy output and the resource availability to meet system peak demand. Ghana has a renewable energy standard (RES) of 10% by 2030. Model results reveal that this RES is feasible across all four scenarios with renewable energy generation growing by 2-4 times its 2024 levels by 2032, and reaching 37-59% of the generation mix by 2040. However, it is important to consider these high penetration levels of renewables with caution given that Ghana's system operators state that penetration levels higher than 10-15% would require additional investment in grid modernization [5].

6.2.4 Non-Served Electricity Demand

An important question is how different installed capacity and generation mixes impact system reliability. I therefore look at total non-served system demand, which is the sum of non-served energy and spinning reserve shortages, under each of the four scenarios (see **Figure 6-4**). As expected, the REF case has the most non-

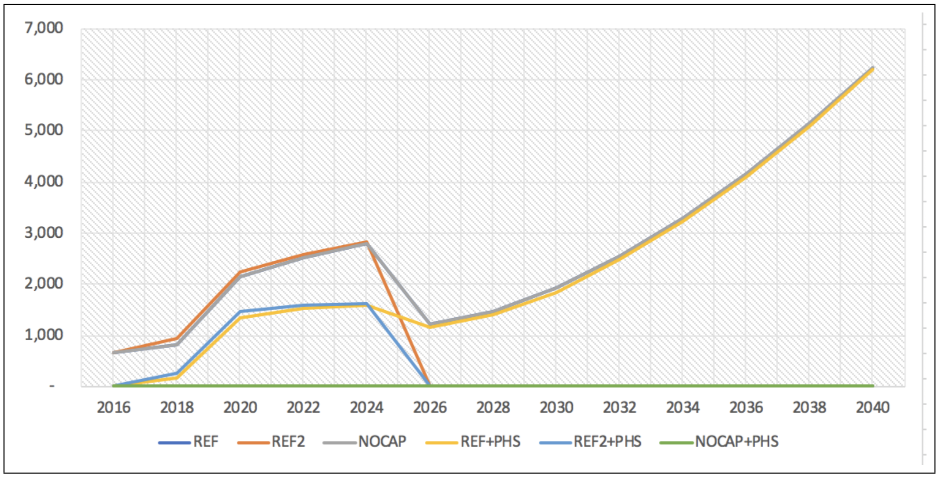


Figure 6-11: Sum of Non-Served Energy and Spinning Reserve Shortages (in GWh)

served demand, and NOCAP+PHS has the least. The REF and REF+PHS cases show significant levels of non- served demand due to the fuel restriction. NOCAP and REF2 have no NSE after 2024, but have significant spinning reserve shortages between 2016 and 2024. PHS can significantly reduce the non-served demand. In the reference case, the addition of PHS reduces non-served demand in early years, reducing it by almost half in 2024. However, it does not help reduce non-served beyond 2024, as it remains about the same as the REF case. Yet, in the REF2+PHS case, the addition of PHS completely eliminates spinning reserve shortages and NSE after 2024. In the cases with no fuel cap, the addition of PHS eliminates non-served demand for the whole period. Both REF2 and REF2+PHS result in no non-served demand after 2024, with REF2+PHS also reducing non-served demand prior to 2024 compared to REF. This suggests that if expansion and integration challenges can be overcome, renewables, particularly when accompanied by PHS, have the potential to reduce or eliminate non-served demand.

Secure and ample fuel supply also reduces non-served demand, as demonstrated with

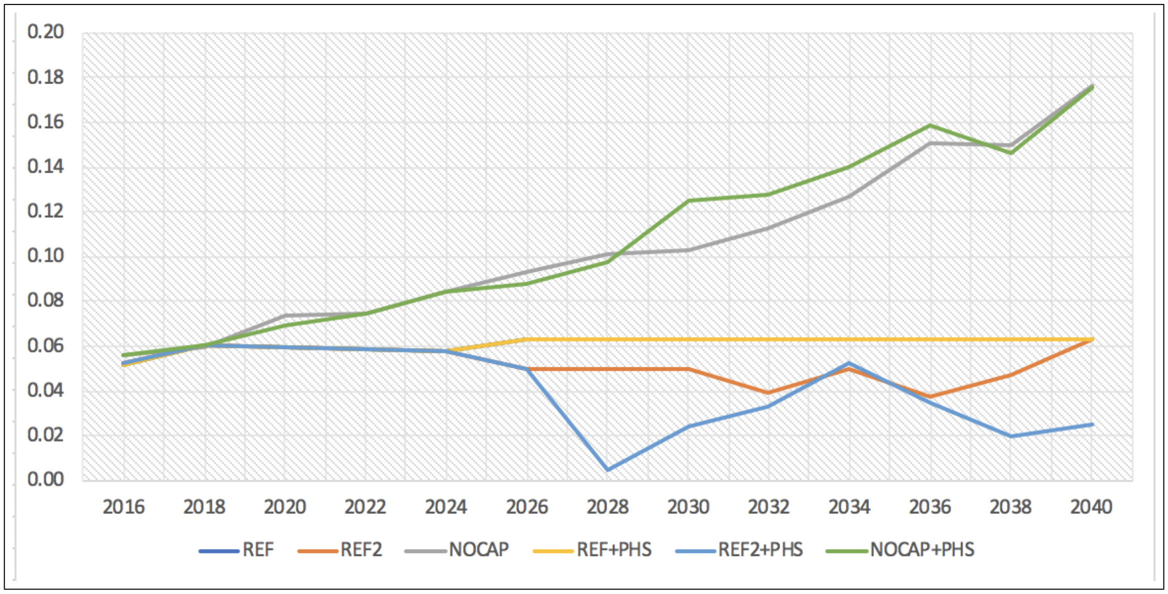


Figure 6-12: Fuel Demand (Quad)

the cases with no fuel cap. The NOCAP case has much less non-served demand than REF out to 2024, and it has zero non-served demand after that. However, the cases with no fuel cap have a much greater dependence on fossil fuels (see **Figure 6-12**). As a result, disruptions to fuel supply could put the system at a significant risk of being unable to meet demand as demonstrated in the past. In the next section, I present the environmental and economic costs of the four scenarios analyzed in this thesis.

6.3 Economic and Environmental Emissions Analysis

6.3.1 Emissions

I measure environmental impacts in terms of CO_2 emissions by comparing the emissions across all cases. It is expected that a generation mix with higher fossil fuel dependence would have higher CO_2 emissions. **Figure 6-13** shows the decrease in CO_2 emissions for REF+PHS, NOCAP and NOCAP+PHS cases relative to the REF case. CO_2 emissions in the REF+PHS case remain unchanged over the whole planning period compared to the REF case. Even though the fuel cap scenarios were primarily designed to mirror existing fuel supply shortages, they also model an electric power system with limits on carbon emissions. Imposing a carbon limit would incentivize investment in carbon-free alternatives such as renewables, which is observed in the fuel cap scenarios.

Despite the high penetration of renewables, emissions significantly increase in the no fuel cap scenarios. By 2040, CO_2 emissions in those scenarios are 125-142% higher than the REF case. These higher emissions are due to the increase in thermal generation and fuel consumption necessary to avoid NSE and spinning reserve shortages (see **Figure 6-11 and 6-13**).

6.3.2 Economic Analysis

One of the main thrusts of this work was to highlight the system costs of various scenarios. **Figure 6-14** shows the relative reductions in total system costs for REF+PHS, NOCAP and NOCAP+PHS relative to REF. The cases without PHS

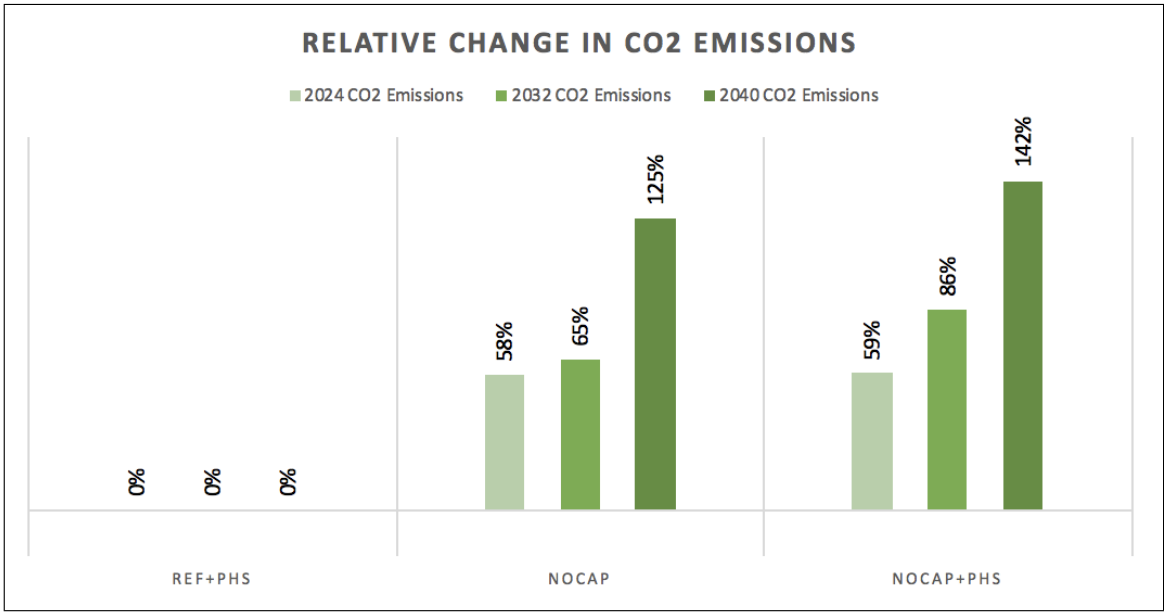


Figure 6-13: Change in CO2 Emissions relative to the REF case

are the most expensive. While the system costs in REF stay fairly high over the planning period because of energy curtailment, there is a reduction in cost in NOCAP. The only difference between REF and NOCAP is that the latter has no fuel consumption restrictions, and because of that NSE is reduced, although operational costs increase. Of the two scenarios with PHS, we see that NOCAP+PHS is much cheaper than REF+PHS because, despite its increased thermal generation and fuel consumption, it has no NSE. Thus, on economic grounds, NOCAP+PHS appears as the least-cost scenario. However, given Ghana's track record on adequate fuel supply, it is fair to assume future fuel shortages are likely, and so caution should be taken when considering expansion plans that rely heavily on fossil fuels.

Overall, these different results highlight how system reliability issues measured by non-served energy and shortages in spinning reserves, and the availability of flexible

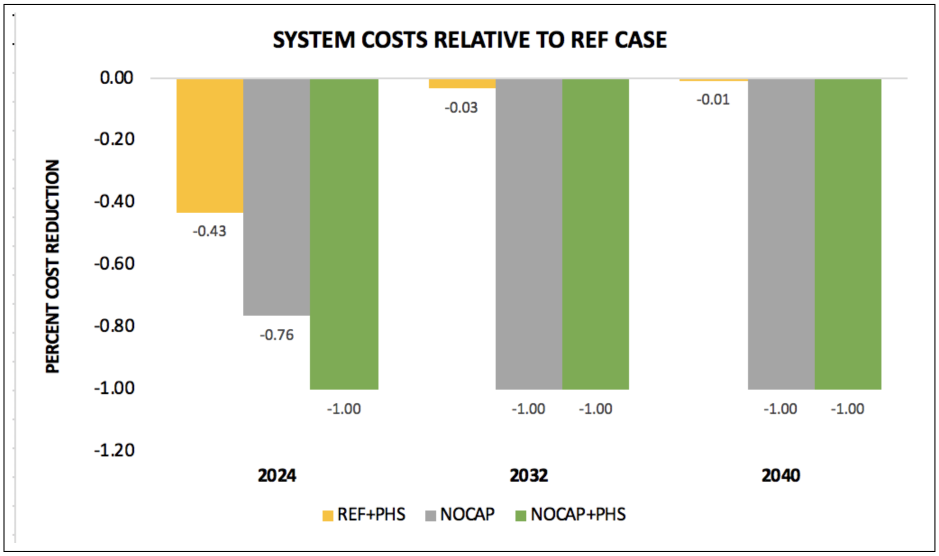


Figure 6-14: Percent reduction in total system costs relative to REF case

technology like PHS significantly impact system costs.

6.4 Additional Observations

It is important to note that variables such as fuel prices, system demand and the cost curves of wind and solar could significantly impact the trends observed in these results. We would expect a higher penetration of renewables in a system with higher fuel prices, and vice versa. Flatter system demand would likely lead to a slower penetration of renewables. Finally, solar and wind were modeled using cost curves with a high mark-up to reflect the risk of doing business in Ghana, so using cheaper costs would further increase their penetration levels.

I presented my results in this chapter, highlighting the role of PHS and fuel supply in obtaining affordable and reliable electric power in the planning period from 2016 to 2040. In the next chapter, I present recommendations on how energy planners and associated parties can strategize to ensure the reliability of Ghana's power system.

Chapter 7

Recommendations and Future Work

7.1 Improving Systems Reliability and Resilience

In this thesis, I explored the electric power sector in Ghana, potential ways the sector could evolve over time, and implications for electricity reliability. In this section, I propose strategies to address the reliability vulnerabilities (as highlighted by the resilience planning process in **Figure 7-1**. In Chapters 2 and 3, I discussed the political and financial challenges facing the power generation sector. In Chapters 4 and 5, I reviewed electricity planning in Ghana, modeling tools that have been applied, and introduced the model I adapted for this work. In Chapter 6, I presented my modeling results, showing the technical constraints and opportunities of various generation expansion pathways, including their implications for non-served energy demand, CO2 emissions and total system costs. The results presented show that

Figure 7-1: Resilience Planning Process [14]

system reliability in Ghana's power generation sector is very sensitive to changes in fuel supply. Additionally, without substantial modernization of the grid, energy systems planners cannot take advantage of the economic and environmental benefits of renewables and flexible technologies like pumped hydro storage (PHS). Successful electricity planning for Ghana's future involves addressing financial, political, technological, economic and environmental challenges and vulnerabilities. In this chapter, I briefly discuss strategies to overcome some of these challenges across the different spheres of the power generation sector.

Based on my research and familiarity with Ghana, the REF scenario is most aligned with the current state of Ghana's electric power sector, which unfortunately has significant amounts of non-served energy. Although unlimited access to fossil fuels could eliminate non-served energy, such a secure and abundant fuel supply is not realistic, and designing the system as though it is (i.e. with a heavy reliance on fossil fuels) would make the system extremely vulnerable to any disruptions in fuel supply. Therefore, the main technical solution I propose is investing in flexible technologies such as PHS, in combination with RETs such as solar and wind to diversify generation expansion. Without solar, wind and PHS, Ghana's power system overwhelmingly consists of hydropower and thermal generation, both of which have recurring vulnerability issues. However, planned projects reveal a reactive approach towards this issue of fuel supply shortages. A $350 million project is currently underway to construct a liquefied natural gas (LNG) import terminal to meet the growing fuel demand of power generating units [95]. In an interview with a high-rank person in Exxon Mobil's Africa strategy team, which operates significantly in the West Africa region, they revealed that this LNG import terminal project is more expensive but quicker than attempting to develop Ghana's domestic gas supply. This solution was not assess in this thesis, but it should be included in future analysis as it is a feasible alternative that many countries adopt as a way to diversify their fuel imports.

Given the socio-economic and political importance of the government's proposed thermal-centric solutions (developing an LNG import terminal or developing Ghana's domestic gas supply), Ghana's future generation expansion is likely to involve political interference. These projects will directly impact system reliability and, by extension, the occurrence of power outages. In this form, rather than energy planners and project developers armed with the financial, technical and technological know-how making planning decisions, government and politics will dictate the electricity planning process.

I propose that instead of doubling down to invest in expensive thermal assets which will only further increase fossil fuel dependency, operating costs and emissions, attention must more seriously shift to a holistic approach to developing Ghana's nascent renewable energy and flexible technology sectors and capabilities. If the government has decided to channel limited public funds to improving system reliability, then I strongly recommend that it invest in industries like wind, solar and PHS. Long-term investments in these technologies can help improve system reliability, and will also result in local capacity development, leading to local jobs, skills and knowledge transfer. The same investment and political clout that was put behind growing Ghana's petroleum sector tremendously since commercial reserves were discovered in 2007 should be directed towards growing the country's renewable energy sector. This includes supporting research projects in the nation's universities, such as the Kwame Nkrumah University of Science and Technology (KNUST), which has conducted numerous renewable resource potential projects, and increasing training for staff in various government agencies like the Energy Commission.

7.1.1 Creating the Environment for Generation Technology Diffusion

The results presented in Chapter 6 show that wind generation may play a crucial role in Ghana's power generation future. Developing Ghana's wind industry will require a different strategy than what has been done for the solar industry. Currently, no wind project exists in Ghana, which means the wind power industry needs to grow quickly and robustly in next few years to capture the projected benefits of investing in this technology. A wide-ranging study by Steffen et. al (2018) stressed the need to consider the important distinction between various renewable energy technologies (RETs) [15]. These differences impact the diffusion of these technology across markets, especially in developing countries that might not have the existing policy or technological infrastructure to support the development of local industries for these products.

Figure 7-2 shows a continuum of increasing technological complexity for solar PV,

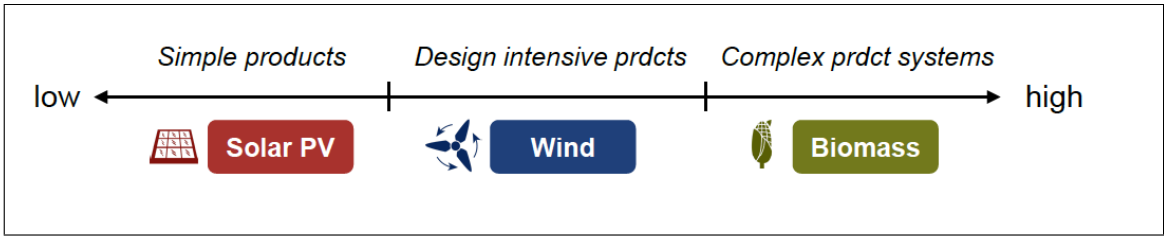


Figure 7-2: Complexity of of renewable-energy product architecture [15]

wind and biomass technologies. Solar PV is relatively easy to introduce to a market, and has been done with success in Ghana. Yet, the development of the local wind industry, which is a major contributor in the generation pathways in our analysis, has stalled because wind power presents challenges uniquely different from those of solar PV [15]. One of these challenges involves obtaining a reliable and accurate country profile of Ghana's hourly wind resources. As mentioned in our modeling approach, I had to use a generic wind profile provided by the government, which lacked regional and seasonal variation. Studies suggest that technologically complex products like wind and biomass require a developed local market to ensure rapid development of the resource [96]. The existence of a local wind industry in Ghana would bring suitable analysis and context that considers the political, economic and cultural challenges and opportunities of the Ghanaian market.

7.1.2 Finance

Beyond investing in specific generation technologies, the state must place more emphasis on a thorough energy infrastructure and development process. The allure of advertising large and flashy projects as political wins may bias project selection. Political and fiscal considerations have led to a pervasive culture of eschewing routine maintenance, in favor of new projects, which leads to the dilapidation of existing infrastructure. There are also often budgetary constraints that reduce and postpone priority of maintenance, which leads to an infrastructure rot. The project selection process should be transparent and include affordability, commercial, and value for money considerations. First, the proposed project must be geared towards a need that is of strategic importance to the electricity sector and the larger economy, with clarity in the project scope, expected outcome and performance standards. Secondly, the project must be affordable to the state and the intended users. Political push back will likely occur, especially if tariffs are introduced or increased. In electricity projects especially, demand and tariff risk analysis must be undertaken early on because this feeds into the overall economic and political feasibility, and longevity of the project [69]. There should be an iterative and flexible project monitoring and evaluation system to incorporate new and relevant information.

Since multilateral banks, especially the World Bank Group, play a major role in infrastructure finance, efforts must be directed towards strengthening the Public-Private Partnership (PPP) framework [9]. PPP agreements can incentivize maintenance, yet, overall, legal and administrative management of PPPs and strategic and prudent project selection falls on the state [69]. To successfully generate affordable and reliable electricity, the sector needs to effectively coordinate across multiple technological, social, economic and financial contexts. I propose the World Bank offer to undertake a review of its PPP Guidance framework and related methodologies to comprehensively identify existing gaps in risk allocation and assuage concerns about its preference for PPPs. Additionally, though infrastructure decisions are often political in nature, the WB can leverage its role in the development world to nudge countries to take a systems level look at investment decisions to develop an investment portfolio that optimizes social, environmental and economic benefits.

Strategies must also be developed around engagement with large financiers like China, Japan and India. As Hannam (2016) stresses in his dissertation, China's rise as a major player in Africa's energy development has reshaped "rule-making authority" in power sector finance, which could very likely dictate the decarbonization path in developing countries [41]. Given this contested authority in power sector finance between the West and China, I propose that Ghana leverage this unique situation to demand finance for projects that diversify its generation mix and modernize its grid to accommodate high penetration of renewables.

7.2 Future Work

This work provided in-depth analysis on the future of generation expansion in Ghana. Yet, there is more analysis that can make our findings more robust. Two major areas of future work are:

- Sensitivity Analysis: Exploring the sensitivity of results to additional important inputs, such as system demand, fuel prices and solar and wind supply curves, will show how robust the insights from this work are.

- System Resilience: Resilience generally refers to the ability to anticipate, respond to and adapt to unexpected disruptions to the normal operations of a system. In terms of a power system, resilience refers to safeguarding against events that threaten the reliable, secure and affordable provision of electricity [14]. Planning to protect the power system against all possible contingencies requires insight into how, when and where disruptions could occur and developing a strategy to mitigate, cope or adapt to those disruptions. Stochastic modeling of the loss of supply can provide insight into the resilience of the country's power system.

Appendix A

Appendix

Table A.1: Existing Power Plants in Ghana [5]

Plant Name	**Online Date**	**Installed Capacity in MW**	**Dependable Capacity in MW**	**Operating Utility**
Akosombo	January 1966	1020	960	Volta River Authority
Kpong	January1982	160	140	Volta River Authority
TAPCO	March 1998	340	305	Volta River Authority
TICO	June 2000	330	320	Volta River Authority
MRP	January 2007	80	70	Volta River Authority
TT1PP	June 2009	110	100	Volta River Authority
TT2PP	June 2010	49.5	45	Volta River Authority
SAPP 1	September 2011	204	180	Volta River Authority
VRA Solar	January 2013	2.5	1.8	Volta River Authority
Bui	June 2013	399	330	Bui Power Authority
CENIT	October 2013	110	100	Cenit Energy Limited
Trojan 1	September 2015	25	22	Trojan Power Limited
KTPP	October 2015	220	200	Volta River Authority
Karpowership 1	December 2015	247	247	Karpower Ghana Limited
BXC Solar	January 2016	20	18	BXC Company
Ameri2016	February 2016	250	230	Ameri
Trojan 2A	February 2016	16.3	16.3	Trojan Power Limited
Trojan 2B	February 2016	16.3	16.3	Trojan Power Limited
GP Chirano	June 2016	33	30	Genser Power
Safisana	September 2016	0.1	0.1	Safisana Company Limited
GP Darmang	December 2016	27.5	25.5	Genser Power
GP Tarkwa	December 2016	35.6	33	Genser Power
AKSA	March 2017	375	375	AKSA Energy Ghana
SAPP 2	March 2017	401	370	Sunon Asogli Power Company

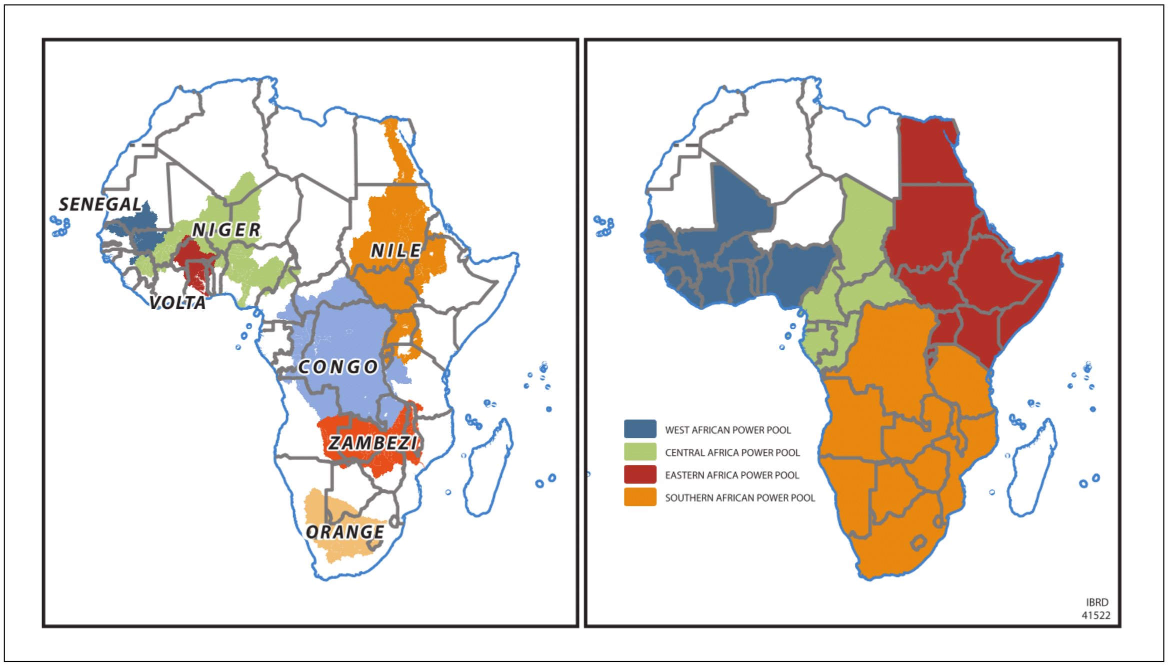


Figure A-1: Power Pools and Water Basins in SSA [16]

Table A.2: Under-Construction Power Plants in Ghana [5]

Plant Name	Online Date	Installed Capacity MW	Dependable Capacity MW	Operating Utility
Cenpower	January 2018	340	340	Cenpower Generation Company Limited
Karpowership 2	January 2018	494	450	Karpower Ghana Limited
Trojan 3	January 2018	49.9	49.9	Trojan Power Limited
Amandi	April 2019	194	190	Amandi Energy
Early Power	September 2019	405.5	377.5	Early Power
Ameri2021	February 2021	250	230	Volta River Authority

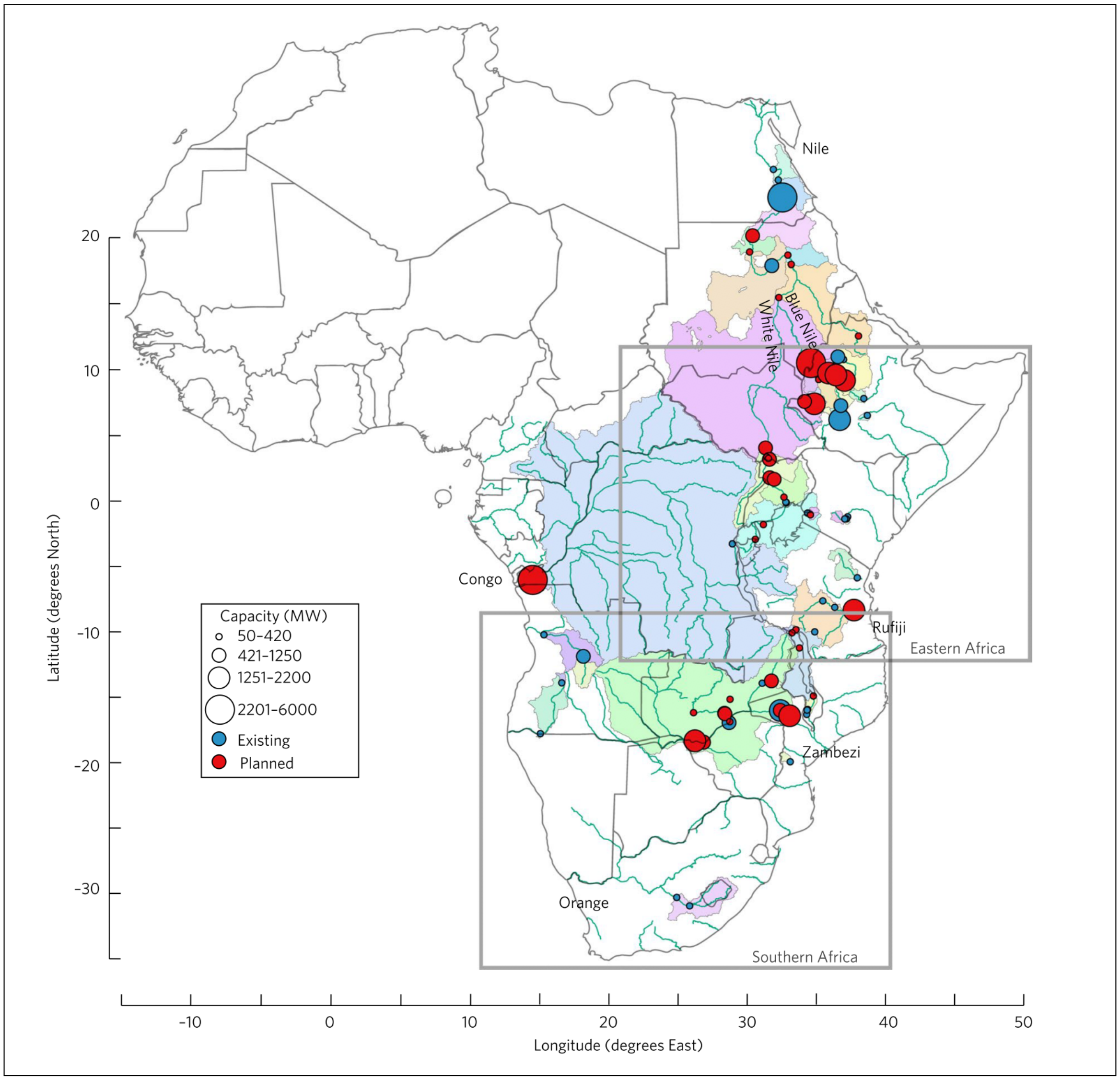


Figure A-2: Existing and Planned Hydro Dams in Eastern and Southern Africa [17]

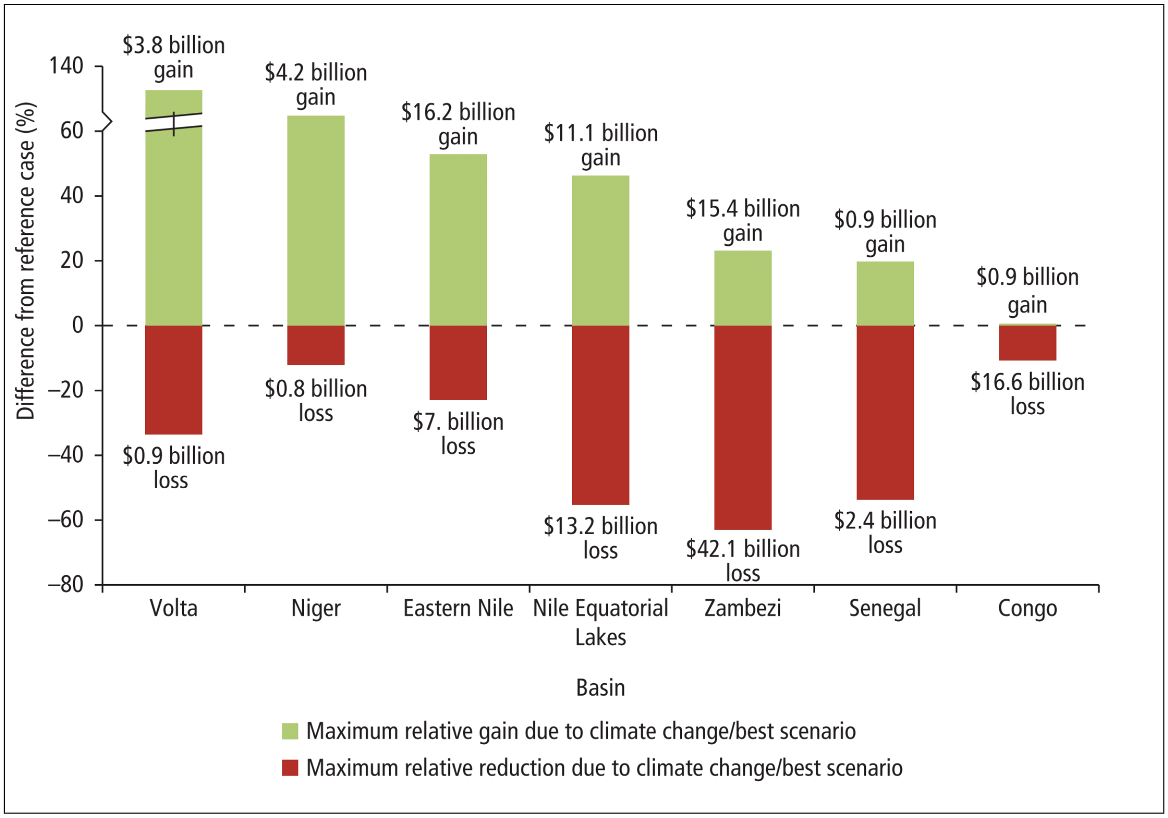


Figure A-3: Relative gains and losses on hydropower due to climate change [16]

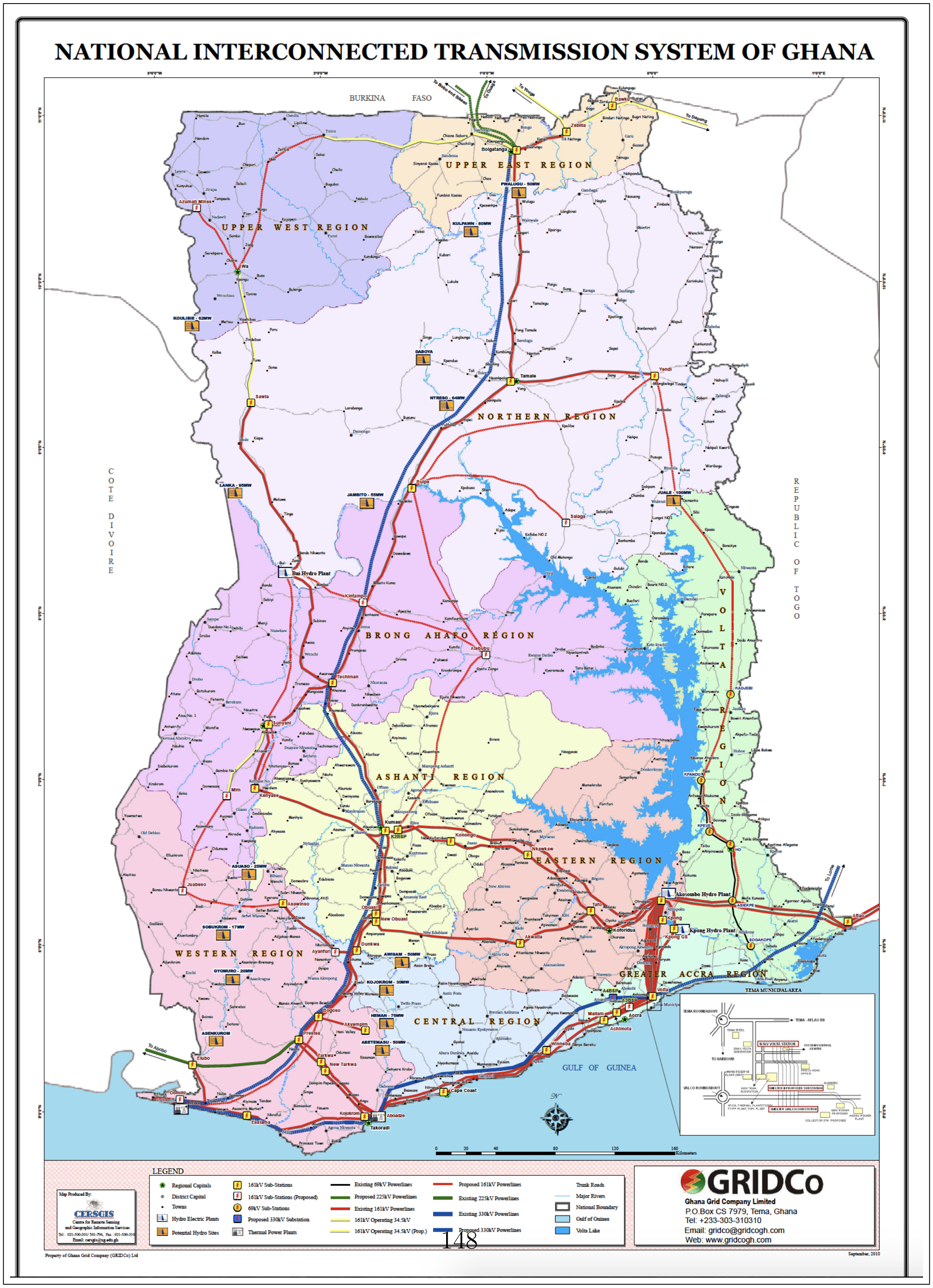


Figure A-4: Ghana's Existing Electricity Transmission Network [2]

Table A.3: Thermal Generation Expansion Outlook for 2016 to 2024 in GW

Elemod Technology	Elemod Region	2016	2018	2020	2022	2024
N01	ONE	0	0.57	0.40	0	0
N01	TWO	0	0.13	0.22	0.36	0.2
N01	THREE	0	0	0	0	0
N02	ONE	0	0	0	0	0
N02	TWO	0	0	0	0	0
N02	THREE	0	0	0	0	0
N03	ONE	0	0	0	0	0
N03	TWO	0	0	0	0	0
N03	THREE	0	0	0	0	0
N04	ONE	0	0.51	0	0	0
N04	TWO	0	0	0	0	0
N04	THREE	0	0	0	0	0
N05	ONE	0	0	0	0	0
N05	TWO	0	0	0	0	0
N05	THREE	0	0	0	0	0

Table A.4: Current and Long-Term Transfer Capability Plans for Ghana's Power System in GW [5]

Region	2016-2018 Non-firm TTC	2016-2018 Firm TTC	2019-2037 Non-firm TTC	2019-2037 Firm TTC
Region 1 to 2	0.740	0.270	1.009	0.391
Region 2 to 1	1.058	0.403	1.089	0.424
Region 1 to 3	0	0	0	0
Region 2 to 3	0.488	0	0.989	0.565
Region 3 to 2	0.531	0.011	0.531	0.152

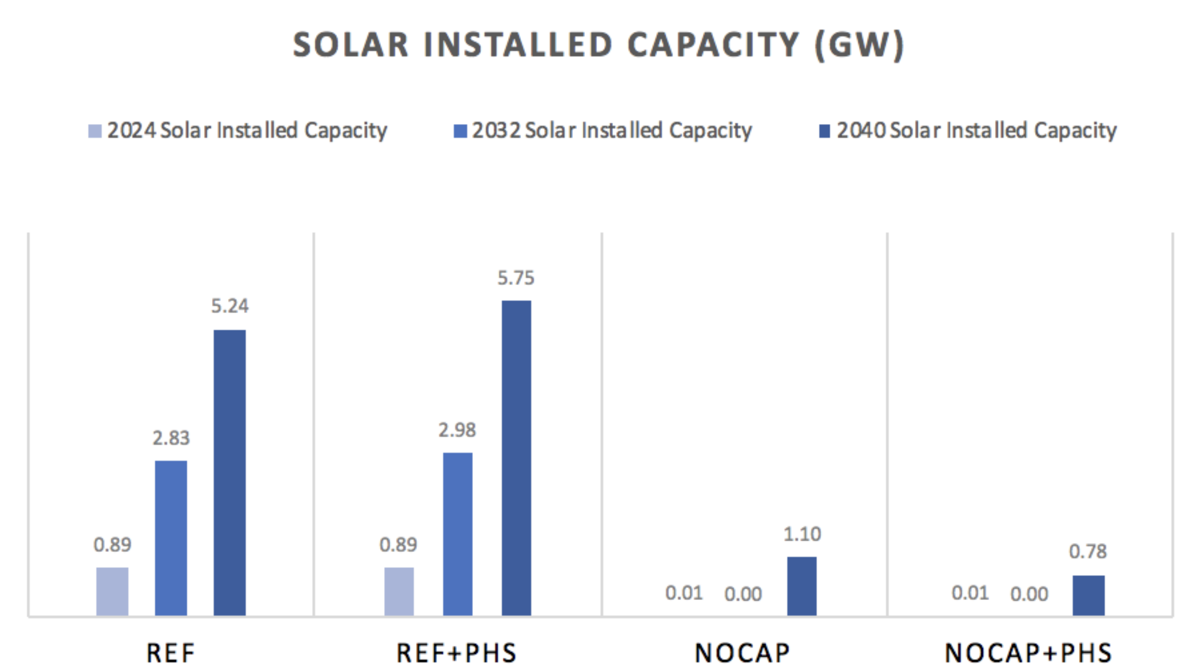


Figure A-5: Solar Installed Capacity in GW

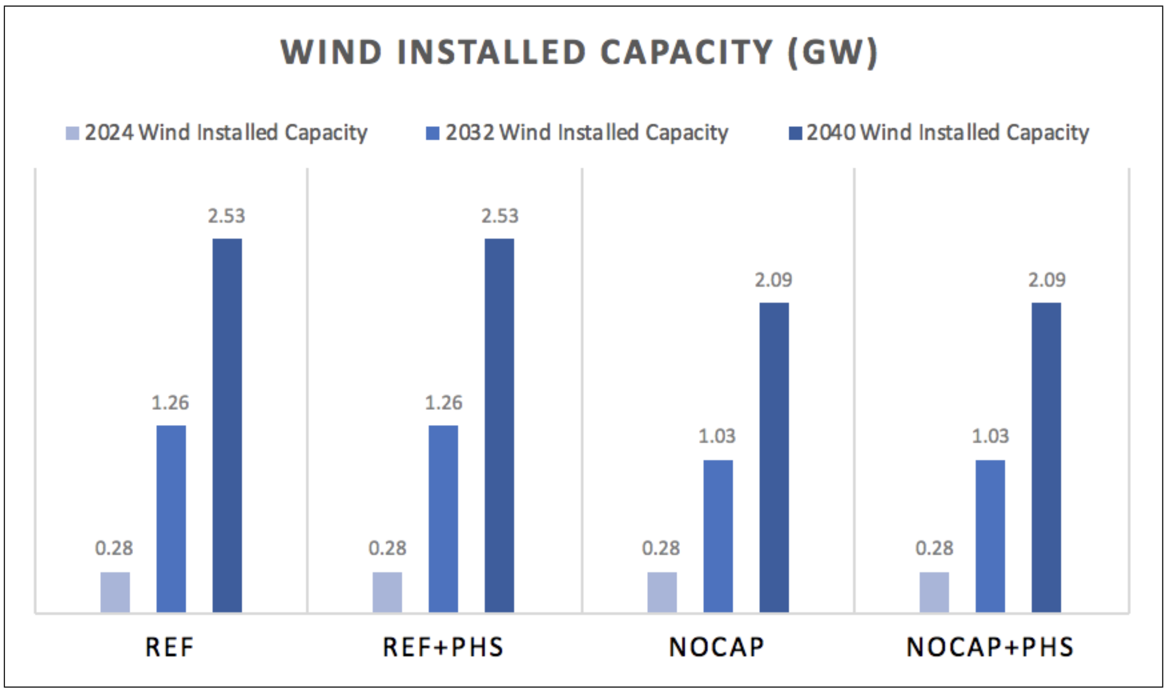


Figure A-6: Wind Installed Capacity in GW

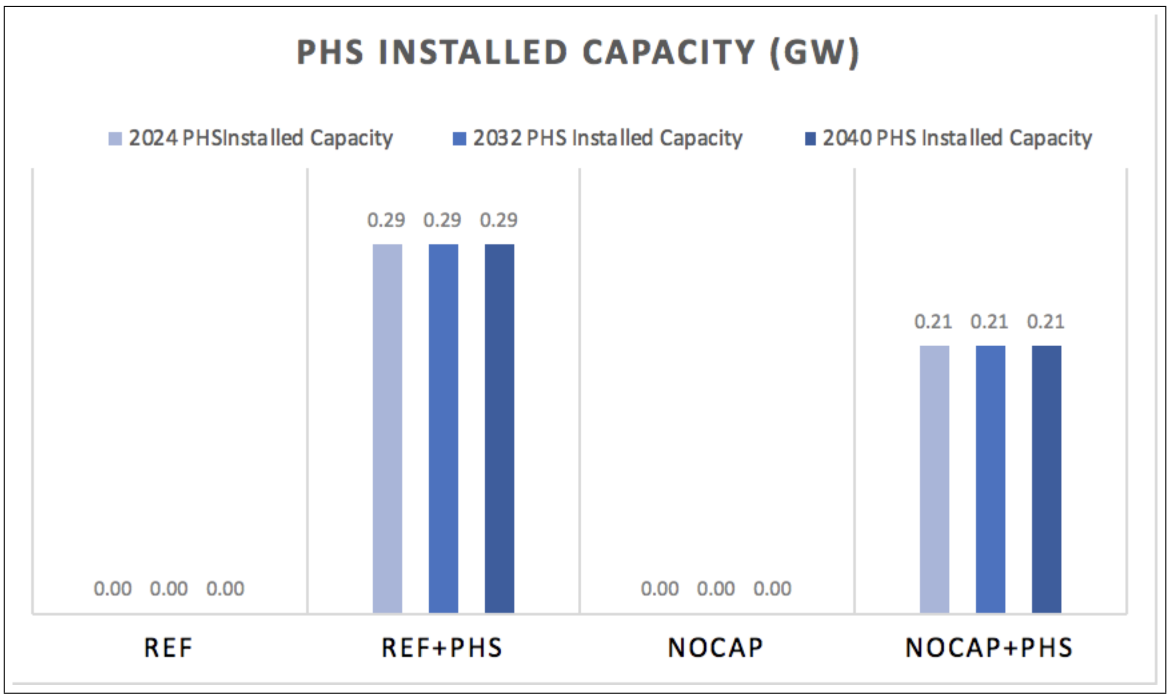


Figure A-7: Pumped Hydro Storage Installed Capacity in GW

Table A.5: List of Acronyms

AMA	Accra Metropolitan Authority
AfDB	Africa Development Bank
ARDL	Autoregressive Distributed Lag Model
BOT	Build, Operate, Transfer
CPP	Convention People's Party
CAIDI	Cumulative Average Interruption Duration Index
DER	Distributed Energy Resources
ECOWAS	Economic Community of West African States
ECREEE	ECOWAS Centre for Renewable Energy and Energy Efficiency
ECG	Electricity Company of Ghana
EC	Energy Commission
GAMS	General Algebraic Modeling System
HOMER	Hybrid Optimization Model for Electric Renewables
IPP	Independent Power Producer
IRP	Integrated Planning Report
kWh	Kilowatt hour
KNUST	Kwame Nkrumah University of Science and Technology
LEAP	Long-range Energy Alternative Planning
MW	Megawatt
MWh	Megawatt hour
MIP	Mixed Integer Program
MSW	Municipal Solid Waste
NREL	National Renewable Energy Laboratory
NAM	Non-Aligned Movement

NSE	Non-Served Energy
NEDCo	Northern Electricity Distribution Company
PAM	Partial Adjustment Model
PPA	Power Purchase Agreement
PURC	Public Utilities Regulatory Commission
PPP	Public-Private Partnership
PHS	Pumped Hydro Storage
ReEDS	Regional Energy Deployment System
RE	Renewable Energy
RES	Renewable Energy Standard
RET	Renewable Energy Technology
SWERA	Solar and Wind Energy Resource Assessment
SHS	Solar Home Systems
SWITCH	solar, wind, conventional and hydro, generation and transmission
SOE	State-Owned Enterprise
SNEP	Strategic National Energy Plan
SSA	Sub-Saharan Africa
SDG	Sustainable Development Goal
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SPLAT	System Planning Test model for Africa
VRA	Volta River Authority
VRP	Volta River Project
WtE	Waste-to-Energy
WAGP	West African Gas Pipeline

WAPP	West African Power Pool
WB	World Bank

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