Developing a Synthetic Electric Grid in Africa: A Case Study in Ghana

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***Abstract*—This paper presents a synthetic power grid test case developed for Ghana, West Africa, that can be used for power systems studies, algorithmic benchmarking, regional research, and educational purposes. Using publicly available data and methods from prior literature, this synthetic grid provides a "realistic but not real" test case. The paper validates the test case and describes possible future extensions. All methods and information sources are documented in the paper. As an illustrative application, the paper analyzes the impacts of five new Ghanaian solar farms on operating costs and greenhouse gas emissions.**

***Index Terms*—Synthetic grid, optimal power flow, geographically accurate, Africa.**

I. Introduction

Since power grids are critical infrastructure, associated datasets are considered sensitive and are often kept confidential. This lack of public access to power systems data can hinder innovation and research productivity [1], [2]. Thus, researchers have developed synthetic grid models to mirror real-world power networks, utilizing publicly available data and the laws of physics to create "realistic but not real" test cases that emulate the performance of actual power grids. This enables large-scale simulations with detailed system models [2]–[7]. Synthetic grids allow researchers to develop algorithms relevant to particular applications. Additionally, without detailed test cases, research studies regarding policy-relevant topics like renewable energy planning and power grid reinforcement may make poorly informed recommendations.

While extensive research has been conducted on synthetic grid creation and development, most of this work has focused on the United States and Europe, e.g., [3]–[6], with little work for developing countries in regions like Africa and Asia. To the best of our knowledge, the only existing detailed synthetic grids for regions outside the United States and Europe are for Saudi Arabia [8], Singapore [9], and South Korea [10]. To address the lack of African test cases, this paper focuses on the developing country of Ghana in West Africa.

Extensive research has been done on synthetic grid creation. Creating synthetic grids involves various techniques and data sources relevant to the particular geographic region and intended applications. For instance, methods for creating a geographically accurate test system for the state of California are detailed in [5], where several sources of publicly accessible electric infrastructure data about generation, load, and transmission lines/parameters are utilized to model the system. We take a similar approach to develop a test case for Ghana. We explore multiple data sources, ranging from research articles, published reports from utility companies in the country, and open-source grid data, to create a grid model that represents the electric transmission network in Ghana as accurately as possible. We complement these with methods used in the prior literature, such as [2], to determine various electrical parameters. The resulting test case is suitable for steady-state analyses like power flow and optimal power flow.

Ghana is an ideal location for synthetic test case creation for developing countries. With limited available hydropower, decline of local natural gas reserves, price volatility of fossil fuels, and increasing electricity demand, the country has a pressing need for diversification of energy sources via nuclear power as well as renewables such as solar photovoltaic (PV) generation [11], [12]. Research on this topic can contribute to achieving energy diversification goals and improving grid security. This, in turn, will support informed decision-making and policy development, ensuring that Ghana's energy system evolves to meet growing demand while improving reliability and reducing dependence on fossil fuels. Moreover, a well-constructed synthetic grid model will serve as a foundation for large-scale simulations and scenario planning, aiding in identifying potential vulnerabilities and optimizing operations.

This paper is structured as follows. Section II describes the creation of the synthetic grid model. Section III validates the model's performance. Section IV presents an illustrative application of this model. Section V concludes the paper.

II. Modeling the Ghanaian Electric Grid

This section describes our approach for compiling information from multiple public sources to create a realistic model of Ghana's electric transmission system. [1]

A. Generation

Ghana's primary electric power sources include hydroelectricity and natural gas, but the country also aims to exploit additional energy sources, such as nuclear and coal power, for a secure future electricity supply [12]. There are currently twenty-five operational power plants in Ghana [14]. We collected data on various parameters for each plant, such as the real power output, reactive power output, generation capacity,

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[1] The test case data is available at https://doi.org/10.5281/zenodo.15148469.

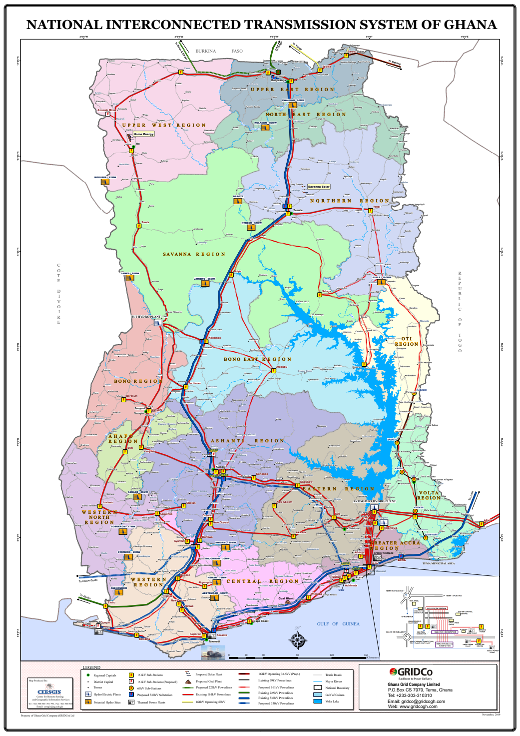


Fig. 1: Ghana transmission system topology [13]

and other unit information of all power plants. For instance, the information in [14] details the generators installed and their capacities. Each power plant was represented as a single generator unit for modeling simplicity. The generators were then assigned to substations based on geographical proximity. Next, we provide a detailed explanation of the processes used to estimate or calculate the generator parameters.

1) Reactive Power Generation Limits: To find the reactive power output range of the hydro and natural gas fueled synchronous generators, we used the scaling factors in [2].

Solar photovoltaic (PV) generators are connected to the power grid through inverters. The output of solar PV inverters is limited by internal voltage, temperature, and current constraints different from that of synchronous generators. Consequently, the reactive power capability curves are unique to the specific inverter-based resource. However, due to a lack of data, we used the inverter datasheet from the Meinenergy plant as a reference for other PV systems in the grid [15]. This datasheet specifies real and apparent power ratings of 300 kW and 330 kVA, respectively. The derived per-inverter reactive power, $Q_c = \sqrt{S_g^2 - P_g^2} = 137.47\,\text{kVAr}$, was then used to estimate the ranges of all the solar plants in the study.

2) Generation Cost: Our generation cost model is based on data from the 2022 Annual Report of the Ghana Grid Company [13]. For the sake of simplicity, we assume a linear cost function. Table I summarizes the operating cost for each energy source used in Ghanaian power plants.

TABLE I: Operating Costs for Different Energy Sources

Plant Type	**Natural gas**	**Hydro**	**Solar**	**Biogas**
Operating Cost (\$/MWh)	71.74	0	0	10

B. Transmission

Transmission lines connect substations across the grid. In addition to defining the topological connections, creating a synthetic grid requires specifying transmission line electrical parameters like series impedances, shunt admittances, and flow limits. This paper uses processes similar to those described in [2]. A detailed methodology is discussed in this section.

To establish the transmission network topology, we use publicly available data obtained from the Economic Community of West African States (ECOWAS) Center for Renewable Energy and Energy Efficiency (ECREEE) [16]. For all transmission lines in the West Africa region, this dataset provides information on the connected buses ("to" and "from" buses) with their corresponding substation names, approximate line lengths (km), and nominal voltage levels (kV). For this project, we extracted all the lines in Ghana as well as lines connecting Ghana to the bordering countries of Togo, Cote d'Ivoire, and Burkina Faso. Since the ECOWAS database contains extensive information on the existing transmission line topology in Ghana, methods used in [2], such as Delaunay triangulation, were not used for determining candidate transmission lines.

Next, we assign values for the electrical parameters of the various lines using the methods described in [2]. A publicly available field report conducted in Accra, Ghana [17] provides detailed transmission line parameters (resistance, capacitive susceptance, and inductive reactance) for select 161 kV and 330 kV lines around the area, allowing us to use accurate parameters in our model for these lines. We then determine the electrical parameter estimates using various assumptions for all other lines not mentioned in the field report.

To illustrate, because we know the voltage level and line length of all transmission lines in Ghana from [16], we assume the same conductor type and construction among all remaining lines of the same voltage level to infer resistance, inductance, and reactance. We obtain information on the conductor type of cable used and the construction from a combination of reports on previous transmission projects in Ghana and standard transmission line characteristics, as provided by [18], [19]. For example, [20] documents project details in the construction of a 161 kV line connecting Obuasi and Prestea, including that the cable used is aluminum-conductor steel-reinforced (ACSR) of the Toucan type. Similarly, [21] details the construction of a 330 kV line across various West African countries using Bison ACSR cable, while [22] describes the technical characteristics of 225 kV conductors used in the region.

With these documents as references, we assume that all lines of the same voltage level use the same cable type and, therefore, have the same per-distance resistance. From [18] and [19], we assume that all lines of the same voltage have the same construction to determine geometric mean distance; for example, 330 kV lines have an interconductor distance of 25 feet [19]. To determine line flow limits, we assumed all 161 and 330 kV lines were rated similarly to the ones mentioned in the field report [17], while other line ratings were determined using max current ratings in standard conductor datasheets such as those in [18]. Using these reports and standard line modeling techniques, we computed the necessary line parameters for each voltage level, as described below.

Total line series resistance R was calculated and corrected to the standard 50 Hz operation frequency used in Ghana through the equation below, where r_d [Ω/km] represents the per-distance value at 60 Hz provided in standard transmission line data sheets [18], b is the number of bundled conductors per phase, and l is the geographical line length taken from [16]:

$$R = \frac{r_d}{b} l \ [\Omega].$$

Inductive (X_L) and capacitive (X_C) reactances were derived from the line capacitance C and inductance L. The related equations are shown below, where geometric mean distance D_m, geometric mean radius R_b, and conductor radius R_b^c were obtained from the aforementioned reference [18] and field reports, as well as reference [19]:

$$C = \frac{2\pi\epsilon}{\ln\left(\frac{D_m}{R_b^c}\right)} \ [\text{F/m}], \qquad X_C = 1/(2\pi f C) \ [\Omega/\text{m}],$$

$$L = (2 \times 10^{-7}) \ln\left(\frac{D_m}{R_b}\right) \ [\text{H/m}], \quad X_L = 2\pi f L \ [\Omega/\text{m}].$$

Finally, we converted the line parameters for the series resistance R, series reactance $x = X_L$, and charging susceptance $b_c = 1/X_C$ to per-unit values using a base power of 100 MVA.

C. Demand

Ghana is a developing country with a growing rate of electricity consumption [23], [24]. The Energy Commission of Ghana reports electricity access rates as low as 30% in many districts across the country [23]. These low levels of electricity access and unreliable electricity supply have stunted Ghana's projected Gross Domestic Product (GDP) by 2% every year [25], indicating the importance of electricity availability for economic availability. We combine data from multiple sources to represent the electricity demand across Ghana accurately in our synthetic model.

We derive the proportion of active power demand for each district in Ghana from the Ghana Energy Commission's Energy Profile report [23]. Combining these with the national yearly electrical energy demand, E_d, as reported in [13], we obtain the average electricity demand in megawatts for every district. We convert the total energy consumption to power demand using the formula below:

$$\text{Active Power, } P_d = \frac{E_d \times 1000}{8760}.$$

We then obtain values for the districts' reactive power demands by setting the power factor at 0.95 per the Ghanaian renewable energy grid code [26]. Finally, each district is systematically assigned to a functioning substation based on proximity and the number of districts already assigned.

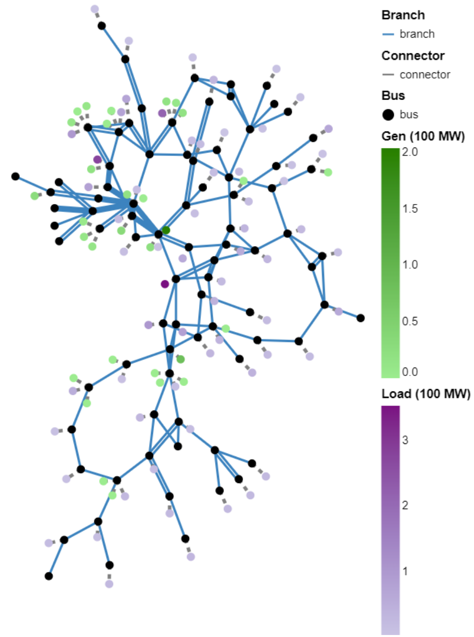


Fig. 2: Ghana synthetic grid topology

TABLE II: Components of the Synthetic Grid Model

Component	Bus	Generator	Line	Load
Count	84	25	160	61

To further mirror Ghana's current electrical demand situation, we provide information on the electricity access rates at each substation in the GitHub repository.[2] The figures are based on the electricity access rates for the individual districts as provided in [23]. This information is crucial for grid expansion planning and economic research studies.

III. Validation of the Synthetic Grid Model

Using all the processes detailed above, we created a representation of the Ghanian transmission grid in the MATPOWER [27] file format. This section describes the test case characteristics and presents validation results based on both topological criteria (degree distribution) and an analysis of optimal power flow results for this system. All computations were performed using PowerModels [28].

A. Visualization of the Synthetic Grid Model and Topological Validation Criteria

The synthetic network has 84 buses representing substations in Ghana and border towns in neighboring countries, including Cote d'Ivoire, Togo, and Burkina Faso. Table II summarizes the components of the model, and Figure 2 shows a conceptual plot of the grid topology. Figure 3 shows a geolocated representation of the synthetic grid.

Twenty-five operating generators with a total installed capacity of 7055 MW provide power for sixty-one load buses with a total real power demand of 2648 MW. Generator

[2]See https://doi.org/10.5281/zenodo.15148469.

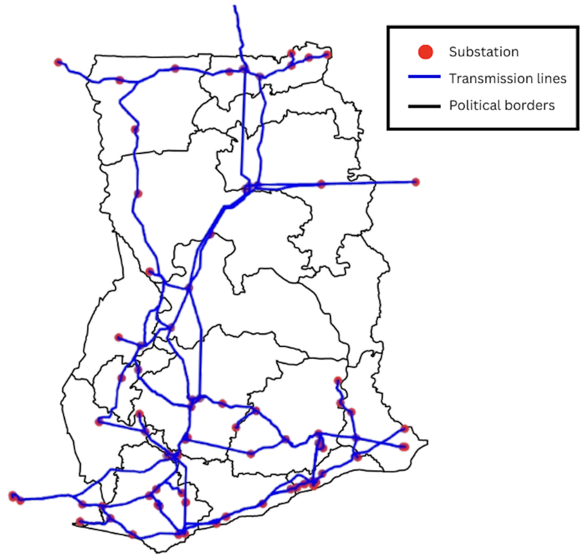


Fig. 3: Geolocated representation of the Ghana grid

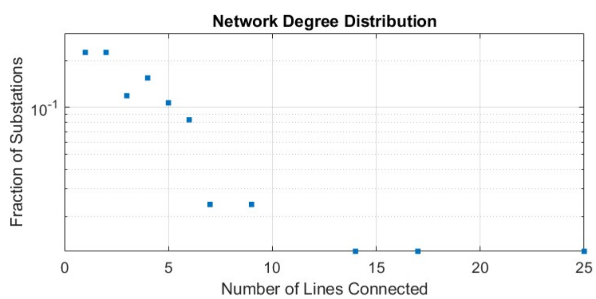


Fig. 4: Logarithmic node degree distribution exhibits an approximately exponential decline

capacities by fuel type are shown in Table III, reflecting the thermal and hydropower dominance as discussed in [12].

One important metric in synthetic grid validation is the node degree distribution across substations [5]. As shown in Fig. 4, the node degree distribution of the synthetic Ghanaian network shows that most substations have between one and four incident lines. While the peak value of one to two neighboring nodes differs from the 2.5 to 3 node peak value that is typical of real networks in the United States, the distribution's downward exponential tail aligns with real network trends [29]. Statistical comparisons between the synthetic network and Ghana's real network are constrained by scarce samples of real-world networks outside North America and Europe and limited publicly available data on Ghana's grid, with most data for this synthetic network sourced from the

TABLE III: Generator Capacity by Type

Type	Biogas	Solar	Hydro	Natural Gas
Count	1	6	4	14
Capacity (MW)	0.1	98–121	1370–1584	3544–3800

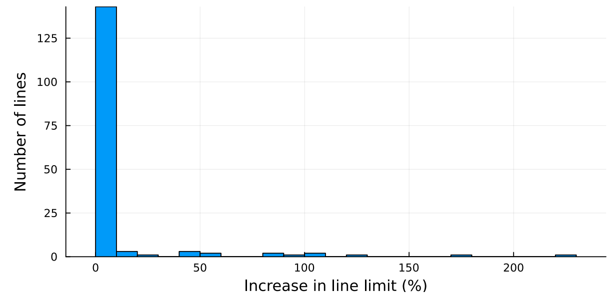


Fig. 5: Percentage of line relaxation for DCOPF feasibility

ECREEE database [16], [30]. The three substations in Fig. 4 connected to 14, 17, and 25 lines are located in Akosombo, Bolgatanga, and Volta, respectively, situated in the Greater Accra region of Ghana. This region has the highest population and electricity access rates (96.1%) [24]. This is also seen in Figs. 1 and 2, where the high concentration of branches and nodes represents the Greater Accra region and Akosombo, the location of Ghana's most significant hydroelectric power plant, the Akosombo Dam [24]. To summarize, the network degree distribution has similar characteristics overall to those in other power grids, with differences in the upper tail behavior that are consistent with specific geographic characteristics.

B. Branch Thermal Limit Revisions

The initial estimates obtained for the branch flow limits did not allow for a feasible solution to the DC Optimal Power Flow (DCOPF) problem. This was due to congestion in several of the system's transmission lines.

To address this, we relax the DCOPF problem's line flow constraints with penalized slack variables to compute a minimum perturbation to the line flow limits to achieve feasibility. This effectively provides the *extra* line thermal capacity needed to achieve a feasible solution to the DCOPF problem. We calculate these slack variables under slightly overloaded conditions to enable optimal performance of this test case at peak demand and in future scenarios of demand growth.

The percentage increase in the line capacities, as indicated by the magnitude of the slack variables, is shown in Fig. 5. The majority of the line flow limits, roughly 90%, need to be relaxed by less than 5% of their original estimated values. Contrarily, five lines required relaxing by more than 100% of the initially estimated values. These lines are located in the Ashanti region, the region with the highest population and the commercial capital of the country—the line requiring the highest relaxation needed for the transmission linking the Akosombo Dam to Kumasi substation. It is worth noting that the initial thermal limits for these lines were only an estimation and were outside the specific values reported in the field report [17].

C. DC Optimal Power Flow

We use the PowerModels package [28] to compute the DC optimal power flow. The solver Gurobi computes an optimal solution in 0.001 seconds [31]. The transmission line flows as

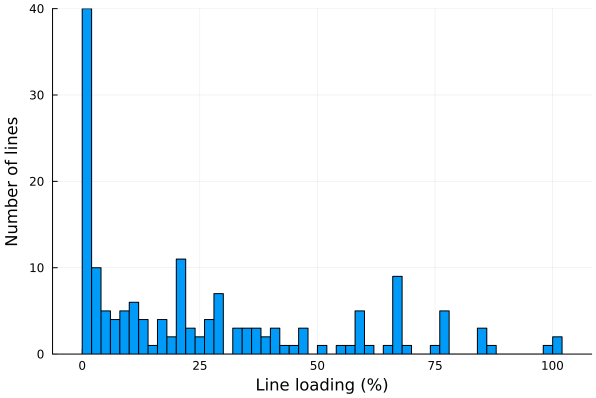


Fig. 6: Percentage loading of the transmission lines

a percentage of their ratings are shown in Fig. 6. The results in Fig. 6 match expectations that the DCOPF solution has only a small number of lines near their flow limits.

IV. Illustrative Application: Solar Expansion Impact Assessment

To demonstrate a potential application of this synthetic grid model, this section presents an illustrative example of how the model can be used to assess the impact of solar expansion in Ghana. Using a multi-period DCOPF simulation, we analyze the grid's performance under two scenarios. By comparing the DCOPF solutions for the two scenarios, we examine the impact of increased solar installations on operating costs and carbon emission reductions.

1) Scenario 1: We first consider the current electricity generation profile as described in Section II-A1, which includes natural gas, solar, and hydro units.

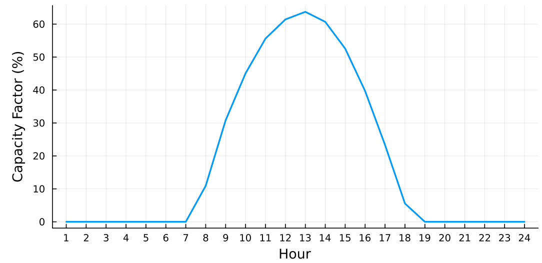
2) Scenario 2: We next augment the current generation mix with five solar farm units projected to be completed in Ghana by 2030 [32]. These solar farms are distributed across multiple regions in the country and have various capacities, as shown in Table IV. We did not include any battery storage installations.

A. Load and Solar Profiles

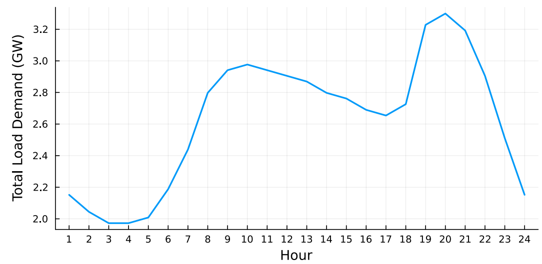
To estimate the outputs of the solar plants in the electricity network, we use the PVWatts Calculator [33], an online simulation tool that, for a specified location, provides hourly AC power outputs for solar panels across a year. For the load profiles, we use the diurnal pattern of the Kenyan electricity demand as provided in [34] to estimate the Ghanaian system. The patterns were scaled to match the Ghanaian peak values and average national electrical energy consumption as reported in [13]. The profiles obtained for a day from these sources are shown in Fig. 7.

TABLE IV: Solar photovoltaic installations in Ghana projected to be completed by 2030

Solar Plant	Location/Region	Capacity (MW)
Meinenergy	Bono East	1000
Bole	Northern	250
Tianjin	Savannah	130
Blue Power Energy	Northern	100
Nante	Bono East	70



(a) Solar generation profile over 24 hours.



(b) Electricity demand profile over 24 hours.

Fig. 7: A representative day of solar generation and load demand profiles

B. Results

Table V shows the cost of meeting electricity demand for a day under the two scenarios and extrapolated for a year using the assumption of the same patterns each day of the year. The results show that installing the five additional solar farms provides annual operational cost savings of $167 million.

The solar farms also yield significant reductions in carbon emissions. Assuming a 40% thermal efficiency of turbines [35], a lower heating value (LHV) of natural gas of 50 MJ/kg [36], and complete combustion to CO_2, we estimate the emissions per megawatt-hour (MWh) of electricity generated from a natural gas power plant to be approximately 500 kg CO_2 per MWh. Consequently, we estimate a total CO_2 emission reduction of 76,800 metric tons (tonnes) of CO_2 per day. This is equivalent to approximately a 25% reduction in emissions each day.

TABLE V: Operational cost from the current generation profile (Scenario 1) vs. the future profile with solar generation (Scenario 2)

	Daily Cost	Yearly Cost
Scenario 1	$1.81 million	$659 million
Scenario 2	$1.35 million	$492 million

TABLE VI: Comparison of daily natural gas (NG) generation and carbon emissions between Scenario 1 and Scenario 2

	NG Generation (GWh)	Daily CO_2 Emissions (tons)
Scenario 1	25.2	$302,200$
Scenario 2	18.7	$225,400$

V. Conclusion and Future Work

This paper describes the creation of a synthetic test case for the Ghanaian electric grid. This test case is developed using multiple sources of publicly available data to replicate the actual system as accurately as possible. To validate the performance of this model, we perform a topological analysis (nodal degree distribution) and study the characteristics of a DC optimal power flow solution (after relaxing the line flow limits to achieve feasibility).

We demonstrate the value of such a test case by conducting a solar expansion impact assessment in Ghana. We compare two scenarios, the current generation profile and a projected generation profile after the commissioning of five new solar plants. The results show that installing new plants could save Ghana close to $\$167$ million annually in terms of operating costs and reduce daily CO_2 emissions by $76,800$ metric tons.

To the best of our knowledge, this test case is the first of its kind for a region in Africa. Since many of the data sources compiled for this Ghana test case also provide information on other countries, the work underlying this test case provides a foundation for creating additional test cases for other geographic regions outside of the United States and Europe. Leveraging the Ghana test case and other synthetic grids, our future work plans to study the intersection of electric power and economic development for various developing countries.

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