Optimal Location of Thermal Power Plants: Closer to Demand Centers or Fuel Depots?

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https://dx.doi.org/10.4314/ajmr.v32i2.2

Abstract

The location of a thermal power plant in a country with dispersed demand centers and limited fuel supply sources is an important decision as it greatly impacts electricity supply cost. This study develops an optimization model to support decision making concerning the location of new and existing thermal plants by a centralized planner. The model offers a platform for decision makers to navigate the trade-off between locating a thermal plant either close to fuel depots to reduce fuel transportation cost or close to demand centers to reduce transmission losses and cost. The proposed model is inspired by the decision of the government of Ghana to relocate an existing thermal plant close to a major demand center yet far away from its fuel source. The model is unique as hitherto such decisions have been analyzed mainly using a Multi Criteria Decision Making model that is unable to accurately capture the magnitude of the important factors. Results from applying the model to the relocation problem of the government of Ghana while supportive of the government's decision, also sees the cost of electricity supply increasing by about 0.06% (roughly US$1.5 million annually over a 10-year period). A suggested relocation by the model will reduce electricity supply cost by about 0.1% compared to the government's decision.

Key words: Demand centers, fuel depots, location, transmission cost, transmission losses.

1.0 Introduction

This research was motivated by the announcement of the Government of Ghana (GOG) in 2021 to relocate a 250 MW thermal power plant from the country's coastal region to a place close to the second largest city located about 250km away in a bid to reduce transmission losses and stabilize electricity supply to the northern part of the country (Dapaah, 2022). The announcement of the relocation decision generated heated debates between those in favour and against. Proponents of the decision, such as the Volta River Authority (VRA), a government institution in charge of electricity generation, argued that the relocation is critical to the provision of electricity to the middle and northern parts of the country and promises to boost electricity export in the West African sub-region. Opponents, however, argued it is a politically motivated decision which will lead to high cost of electricity supply (Zurek, 2022). The Africa Centre for Energy Policy (ACEP) as well as the main opposition party raised issues with the cost of relocation and warned that such a move could exacerbate the financial woes of the energy sector (ACEP, 2022). Opponents further warned of the associated fuel transportation costs since the plant will be located far away from its fuel source. The debate raged further when the GOG signed a contract to build a new 350MW thermal plant (Abbey, 2023) also to be located close to the second largest city. This contract added to the suspicion of GOG making politically motivated decisions since the location in question (for both the relocation and the new plant) is in the stronghold of the ruling governing party. Interestingly, prior to these two major decisions, all thermal plants in Ghana have been located along or close to the coast where fuel for the power plants is first delivered.

This is an interesting and classic case of a facility location problem when demand centers are far away from where a power plant sources its fuel. For such demand centers, a trade-off must be made between siting the plant closer to the fuel source and transmitting the electricity generated to the demand centers and siting the plant close to the demand centers and transporting the fuel to where the plant is located. In the end, since all that matters is electricity delivered to the consumer, this research intends to analyze the location problem based on the cost of electricity supply. If the cost of electricity supply under the GOG's location plan is not significantly different from that under the status quo, then the GOG's decision cannot be necessarily classified as politically motivated especially if it can help improve the quality of electricity supply. The issues under contention are encountered on a regular basis in less endowed countries, especially when electricity demand from constituents of a ruling party increases significantly and the government faces political pressure to address it. This research therefore attempts to provide a method that considers the major factors in such a facility location problem as faced by GOG. Several costs are considered, including cost related to transmission of electricity, transmission losses, fuel transportation, and relocation. Thus, the research develops an optimization model where the objective is to minimize the cost of electricity supply of a country based on the optimal location of the generation plants at the central planner's disposal. The developed optimization model can be used to support the location of new and the relocation of existing thermal plants. The model will be helpful especially to less endowed countries where thermal generators due to their less capital cost (relative to other sources such as hydro) are a very attractive choice (Afful-Dadzie et al., 2017). The rest of the paper is organized as follows. A literature review is presented in section two followed by the methodology in section three. This is then followed by a case study involving Ghana in section four. Section five presents the results of the case study followed by a conclusion in section six.

2.0 Literature Review

Location problems are well studied in the literature and are mostly aimed at addressing the question of where an economic activity, for example a factory, should be located and why. Two theories, the Alfred Weber's location theory (also known as the least cost approach), and the August Losch's theory of location serve as the foundation for the location problem studied in this work. Weber's theory of industrial location at a minimum, bases the location decision of a goods-producing firm on transportation and labour costs. It asserts that a firm must be located close to the market and raw material sources (i.e. geographical context) in a manner that minimizes transportation costs of raw materials and finished products. For example, a thermal plant could be located close to demand centers such that transmission cost and losses are minimized or close to a fuel depot such that the transportation cost of the fuel for electricity generation is minimized. Weber's theory, however, does not explicitly factor into account demand. Losch's theory on the other hand places much emphasis on demand or sales and considers locating an industry in an area generating the highest sales revenue. In the electricity sector for instance, Losch's theory will demand that a thermal plant is located close to areas of high demand, such as industrial zones and cities.

Several studies have been conducted on the location of power plants. However, these have mainly been focused on renewable energy technologies such as solar, wind and biomass, with very few on thermal power plants. Given that many less developed countries tend to favour thermal plants due to their affordability in terms of acquisition, it is important that research on location of thermal power plants is given much attention. In general, studies on the location of power plants either approach the analysis using a Multi-Criteria Decision Making (MCDM) or an optimization model. MCDM approaches tend to dominate and are popular among studies on location of renewable energy generators. Studies that employed MCDM based approaches include Wang and Xin (2011), Sun and Qin (2015), Kashawn, Solange, and Legena (2022), Choudhary and Shankar (2012), Siefi, et al. (2017), Gumussoy, Onen, and Yalpir (2024), Azevêdo, Candeias, and Tiba (2017).

The popularity of MCDM techniques stems from its ease of application where all that is needed is the ability to rate a factor between 0 and 100 or 0 and 1 on how good or bad a factor is in relation to a chosen location. Unfortunately, this is also one of its many shortcomings. An MCDM method is unable to explicitly consider the magnitude of quantitative factors, uncertainty in factors, and multiperiod considerations. In addition, an MCDM method cannot explicitly consider the fact that a power plant can be used to serve more than one demand center. Furthermore, the output from an MCDM method cannot be easily translated into a monetary figure to understand the overall benefit or cost thereof arising from the choice of location. However, these shortcomings involving important considerations in thermal power plant site selection can easily be accounted for with the use of an optimization model. Few studies have employed optimization techniques for the location of power plants. Among these, the seminal paper by Ravindran and Hanline (1980) used a Mixed-Integer Linear Programming (MILP) optimization to determine the best optimal site choice for a coal blending plant, whereas Ilbahar et al. (2021) uses a Fuzzy Linear Programming to optimize the location of a waste-to-energy plant. The major factors considered by these authors include fixed and variable cost of transporting fuel to the plants, distance between cities, annual investment of plant capacity cost, annual operating and maintenance cost, and unit price of electricity. Rentizelas and Tatsiopoulos

(2010) also applied a multistage Non-Linear Programming optimization, Genetic Algorithms, and Sequential Quadratic Programming models for the optimal location of a bioenergy plant, whereas Duarte et al. (2014) and Xie, Zhao, and Hemingway (2010) used a Mixed-Integer Linear Programming (MILP) model to analyze the selection of the best location for a biofuel plant. Among the factors considered by these authors include equipment operating and maintenance cost, fixed and variable investment cost of electricity transmission line, fuel transportation cost from a chosen site, electricity transmission cost, and percentage of electricity transmission losses.

The studies in the literature that employ optimization techniques for power plant location mainly focus on location of new power plants without considering relocation of existing plants. Many of these studies do not also explicitly capture transmission losses in the amount of electricity delivered. This paper analyzes the thermal power plant location problem considering these and other important factors such as proximity of power plant locations to demand centers and fuel sources.

3.0 Methodology: Thermal Power Plant Location Model

The optimization model for the location and relocation of thermal power plants is presented next. Table 1a, 1b and 1c presents the nomenclature detailing the meaning of the decision variables and parameters of the model. A simple schematic diagram of three power plants, three fuel depots, three location sites, and three demand centers, depicting the setup of the location problem analyzed in this research is also shown in Figure 1. Note that within the planning period, Figure 1 is meant to be expanded with new power plants to meet increasing future demand. These future plants will also be considered for location at one of the candidate sites.

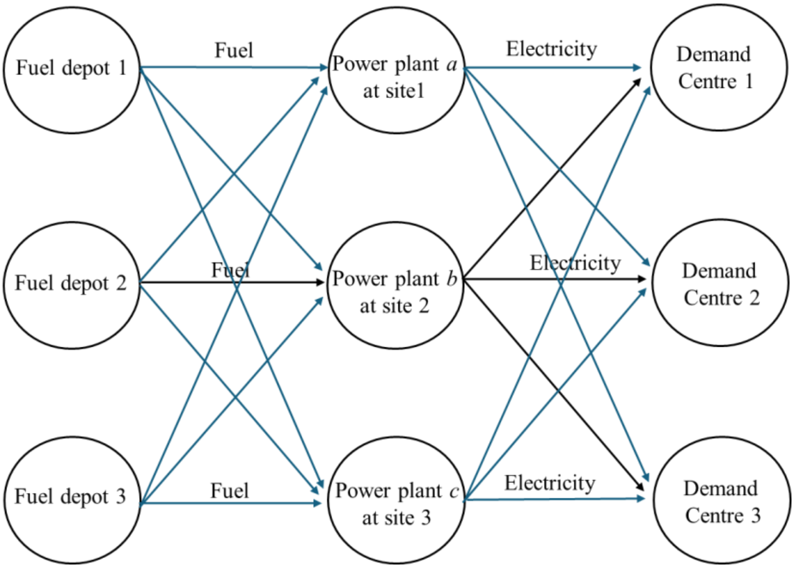

Figure 1: A network diagram of a power system made up of three thermal plants located at three different sites, drawing fuel from three depots to generate electricity for three demand centers

Table 1a: Nomenclature

	Indices
i	Set of existing thermal power plants
p	Set of future thermal power plant types
h	Set of hydro power plants
j	Set of demand centres
k	Set of fuel depots
n	Set of candidate sites
t	Set of years within the planning period
	Decision variables
$\boldsymbol{X_{in}}$	Binary variable indicating whether plant *i* is to be relocated to site *n*
$\mathbf{Y_{injt}}$	Power transmitted by existing thermal plant *i* (relocated to site *n*) to demand center *j* in period *t* [MWh]
$\mathbf{Y_{pnjt}}$	Power transmitted by future thermal plant *p* located at site *n* to demand center *j* in period *t* [MWh]
$\mathbf{Y_{hjt}}$	Power transmitted from hydro power plant *h* to demand center *j* in period *t* [MWh]
$\mathbf{Z_{inkt}}$	Quantity of fuel sourced by existing thermal plant *i* (relocated to site *n*) from fuel depot *k* in period *t* [MMBtu]
$\mathbf{Z_{pnkt}}$	Quantity of fuel sourced by future thermal plant *p* (located at site *n*) from fuel depot *k* in period *t* [MMBtu]
$\mathbf{G_{pnt}}$	Number of thermal plant type *p* to be sited at location *n* in period *t*
$\mathbf{W_{pnt}}$	Total capacity of future thermal plant type *p* to be located at site *n* in period *t* [MW]

Table 1b: Nomenclature

	Parameters
TC	Cost of transmitting 1MWh of power over a unit distance [$/MWh/km]
v	Percentage of transmission loses over a unit distance [%]/km
$\mathbf{CO_{it}}$	Variable operating and maintenance cost of existing thermal plant *i* in period *t* [$/MWh]
$\mathbf{CO_{pt}}$	Variable operating and maintenance cost of future thermal plant type *p* in period *t* [$/MWh]
$\mathbf{CO_{ht}}$	Variable operating and maintenance cost of hydro plant *h* in period *t* [$/MW]
$\mathbf{CC_{i}}$	Annualized capital cost of existing thermal plant *i* [$/MW/Year]
$\mathbf{CC_{p}}$	Annualized capital cost of future thermal plant type *p* [$/MW/Year]
$\mathbf{CC_{h}}$	Annualized capital cost of hydro plant *h* [$/MW/Year]
$\mathbf{FT_{i}}$	Annualized fixed operating and maintenance cost of existing thermal plant *i* [$/MW/Year]
$\mathbf{FT}_{\boldsymbol{p}}$	Annualized fixed operating and maintenance cost of future thermal plant type *p* [$/MW/Year]
$\mathbf{FT_{h}}$	Annualized fixed operating and maintenance cost of hydro plant *h* [$/MW/Year]
$\mathbf{W_{i}}$	Capacity of existing thermal plant *i* [MW]
$\mathbf{W_{h}}$	Capacity of hydro plant *h* [MW]
$\boldsymbol{W_{p}^{max}}$	Maximum rated capacity of future thermal plant type *p* [W]

Table 1c: Nomenclature

$\mathbf{CF_{it}}$	Capacity factor of existing thermal plant *i* in period *t* [%]
$\mathbf{CF_{pt}}$	Capacity factor of future thermal plant type *p* in period *t* [%]
$\mathbf{CF_{ht}}$	Capacity factor of hydro plant *h* in period *t* [%]
$\boldsymbol{\eta_{it}}$	Thermal efficiency of plant *i* in period *t* [%]
$\boldsymbol{\eta_{pt}}$	Thermal efficiency of plant type *p* in period *t* [%]
$\mathbf{MTG_{it}}$	Minimum electricity generation by existing thermal plant *i* in period *t* [%]
$\mathbf{MTG_{pnt}}$	Minimum electricity generation by future thermal plant type *p* located at site *n* in period *t* [%]
$\mathbf{MHG_{ht}}$	Minimum electricity generation by hydro plant *h* in period *t* [%]
$\mathbf{E_{jt}}$	Amount of electricity demanded by demand center *j* in period *t* [MWh]
Q	Cost incurred for transporting 1 MMBtu of natural gas over a unit distance [$/MMBtu/km]
$\mathbf{B_{in}}$	Cost of relocating existing thermal plant *i* to candidate site *n* [$]
$\mathbf{L_{nj}}$	Distance between candidate site *n* and demand center *j* [km]
$\mathbf{L_{hj}}$	Distance between hydro plant *h* location and demand center *j* [km]
$\mathbf{D_{kn}}$	Distance between fuel depot *k* and candidate site *n* [km]
$\boldsymbol{\lambda}$	Number of hours in a year [hours]
C	Conversion rate from MMBTU to MWh (set at 3.412142)

The Mixed Integer Linear Programming (MILP) model for the power plant location problem is made up of Equations (1)-(8). For simplicity, the model considers only thermal and hydroelectric plants. However, the model can be expanded to include other generator types such as solar and wind. Note that only thermal plants are subjected to location or relocation since it is impractical to attempt to relocate a hydroelectric plant. However, the presence of hydroelectric plants influences the location/relocation decision. In addition, it is assumed that a plant can be relocated only once within the planning period, and the relocation if needed will occur at the beginning of the planning period. Each of the different costs in the objective function are discounted to the beginning of the planning period with an interest rate of $\boldsymbol{r}$ % per period.

$$\text{Min } Z = \sum_{t=1}^{T} \frac{1}{(1+r)^{t-1}} \Big[\Big\{ \sum_{j=1}^{J} \sum_{n=1}^{N} \sum_{i=1}^{I} TC * L_{nj} * Y_{injt} + \sum_{j=1}^{J} \sum_{n=1}^{N} \sum_{p=1}^{P} TC * L_{nj} * Y_{pnjt} + \sum_{j=1}^{J} \sum_{h=1}^{H} TC * L_{hj} * Y_{hjt} \Big\} + \Big\{ \sum_{j=1}^{J} \sum_{n=1}^{N} \sum_{i=1}^{I} CO_{it} * Y_{injt} + \sum_{j=1}^{J} \sum_{n=1}^{N} \sum_{p=1}^{P} CO_{pt} * Y_{pnjt} + \sum_{j=1}^{J} \sum_{h=1}^{H} CO_{ht} * Y_{hjp} \Big\} + \Big\{ \sum_{k=1}^{K} \sum_{n=1}^{N} \sum_{i=1}^{I} Q * D_{nk} Z_{inkt} + \sum_{k=1}^{K} \sum_{n=1}^{N} \sum_{p=1}^{P} Q * D_{nk} Z_{pnkt} \Big\} + \Big\{ \sum_{n=1}^{N} \sum_{i=1}^{I} B_{in} * X_{in} \Big\} + \Big\{ \sum_{i=1}^{I} (CC_i + FT_i) * W_i + \sum_{n=1}^{N} \sum_{p=1}^{P} \big(CC_p + FT_p\big) * W_{pnt} + \sum_{h=1}^{H} (CC_h + FT_h) * W_h \Big\} \Big] \quad (1)$$

Subject to the following constraints:

$$\sum_{n=1}^{N} X_{in} = 1 \qquad \forall i \qquad (2)$$

$$\sum_{n=1}^{N}\sum_{i=1}^{I} Y_{injt} * (1 - v * L_{nj}) + \sum_{n=1}^{N}\sum_{p=1}^{P} Y_{pnjt} * (1 - v * L_{nj}) + \sum_{h=1}^{H} Y_{hjt} * (1 - v * L_{hj}) = E_{jt} \qquad \forall j, \forall t \qquad (3)$$

$$\sum_{j=1}^{J} Y_{injt} \leq \lambda * CF_{it} * W_i * X_{in} \qquad \forall i, \forall n, \forall t \qquad (4a)$$

$$\sum_{j=1}^{J} Y_{injt} \geq MTG_{it} * \lambda * CF_{it} * W_i * X_{in} \qquad \forall i, \forall t \qquad (4b)$$

$$\sum_{j=1}^{J} Y_{pnjt} \leq \lambda * CF_{pt} * W_{pnt} \qquad \forall p, \forall n, \forall t \qquad (5a)$$

$$\sum_{j=1}^{J} Y_{pnjt} \geq MTG_{pnt} * \lambda * CF_{pt} * W_{pnt} \qquad \forall p, \forall n, \forall t \qquad (5b)$$

$$W_{pnt} = W_{pn(t-1)} + G_{pnt} * W_{p}^{max} \qquad \forall p, \forall n, \forall t \qquad (5c)$$

$$\sum_{j=1}^{J} Y_{hjt} \leq \lambda * W_h * CF_{ht} \qquad \forall h, \forall t \qquad (6a)$$

$$\sum_{j=1}^{J} Y_{hjt} \geq MHG_{ht} * \lambda * W_h * CF_{ht} \qquad \forall h, \forall t \qquad (6b)$$

$$\sum_{j=1}^{J} Y_{injt} * \frac{C}{\eta_{it}} \leq \sum_{k=1}^{K} Z_{inkt} \qquad \forall i, \forall n, \forall t \qquad (7a)$$

$$\sum_{j=1}^{J} Y_{pnjt} * \frac{C}{\eta_{pt}} \leq \sum_{k=1}^{K} Z_{pnkt} \qquad \forall p, \forall n, \forall t \qquad (7b)$$

$$Y_{inj}, Y_{hj}, Z_{inkt}, Z_{pnkt}, UE_{jt}, W_{pnt} \geq 0 \text{ ; } X_{in} \text{ binary; } G_{pnt} \text{ integer} \qquad \forall i, \forall p, \forall h, \forall n, \forall j, \forall k, \forall t \qquad (8)$$

The overarching goal of the central planner of the power system is to ensure that power plants are placed at locations such that the total cost to the system is minimized. This objective is captured with Eqn (1) which is made up of five major terms (differentiated with curly bracket), namely (1) transmission cost, (2) variable operation and maintenance cost, plus transmission loss costs, (3) fuel transportation cost, (4) relocation cost, and (5) capital cost, plus fixed maintenance and operation cost, in that order. The content in the first curly bracket of Equation (1) is the transmission cost of power taken from the plants (i.e. existing thermal, future thermal, and hydro).

The content in the second curly bracket is made up of two types of cost, the variable maintenance and operation cost (including fuel cost), and the cost of power lost during transmission. The third curly bracket in Equation (1) is made up of the cost of transporting fuel from depots to thermal plants. This cost is divided into two parts, one for existing thermal plants and the other for future thermal plants. The fourth curly bracket of the objective function is the cost of relocating existing plants, whereas the fifth is the fixed and capital cost of the plants.

Since $\boldsymbol{X_{in}}$ is binary, Eqn (2) ensures that a plant is located at only one candidate location site. On other hand, Eqn (3) is the power supply balance constraint for a demand center, where the amount of electricity sent is such that it is enough to meet demand after factoring in transmission losses. Equations 4-8 relate to electricity supply by generators and their technical specifications. For existing thermal plants, Eqns (4a, 5a, and 6a) ensure that the sum of the supply from a thermal plant to the demand centers is within the capacity of the plant. The right-hand-side of Eqn (4a) is multiplied by the binary variable $\boldsymbol{X_{in}}$ to ensure that an existing thermal plant produces electricity from only the site it is located. Note that new thermal plants do not need such a constraint since their generation depends on the capacity accumulated at a site. Also, Eqns (4b, 5b, and 6b) allow for a minimum amount of electricity to be generated by a plant if so desired, for example, perhaps by agreement. The Eqn (5c) serves to track the cumulative capacity of a future thermal plant type (e.g. combine circle gas turbine) at a particular site over time. The constraint capturing the conversion of fuel to electricity by the existing and future thermal plants is given by Eqn (7a) and Eqn (7b) respectively. The model is concluded with the non-negativity constraint of Eqn (8).

4.0 Case study based on Ghana

This section presents a real-world case study applying the location problem model presented in section three. As explained in the introduction section, this research is motivated by the decision of the Government of Ghana (GOG) to relocate an existing thermal plant about 250km away from its current location. This decision attracted several criticisms, especially that there has not been any noticeable problem with regards to the transmission of electricity to the demand center in question. This research therefore sought to analyze GOG's relocation decision using the model developed in section three. The analysis is performed over a 10-year period for better understanding of the short to long term impact of the decision. Since the relocation occurred in 2024, the model has been analyzed for the period 2024-2033. To begin with, a brief background of the electricity generation sector of Ghana is presented.

4.1 Background of the electricity generation sector of Ghana

Ghana is located in West Africa with a population of over 34 million in 2023 (World Bank, 2024). It had a total of 5639 MW (5180 MW) of installed (dependable) capacity in 2023 and generated a total of 24,264 GWh of electricity with a transmission loss of 3.9%. Ghana's electricity generation capacity mix as of 2023 is made up of hydroelectric (28.1%), thermal (69.6%), and solar (2.34%). However, solar accounts for a little over 0.5% of actual electricity generation. Table 2 gives a breakdown of Ghana's electricity generation types and their installed and dependable capacities. Ghana's electricity generation sector comprises of both government and independent power producers. The independent power producers hold at least 50% share of the sector. In 2022, the GOG decided to relocate the Ameri power plant (bold in Table 2) to a location close to the second biggest city in Ghana which is more than 250km away. This is after the ownership of the plant was transferred to the GOG through a Build-Operate-Transfer (BOT) agreement in 2022. Many called the relocation decision politically motivated and one that will lead to an increase in electricity cost since the fuel needed for the generation would have to be transported over long distances. To assuage such concerns, the GOG also commissioned a company to construct a gas pipeline to transport natural gas close to the original location of the plant in question to the new planned location. Fundamentally, this raises the question as to whether it is ideal siting a thermal power plant close to a demand center or to a fuel depot. The GOG's relocation problem is a classic case that can be analyzed using the model from section three. The next sub-section presents the data for the case study.

4.2 Data Presentation

This section presents the data used for the case study including assumed parameters.

4.2.1 Plant Capacity, Efficiency, and Costs

The capacity and efficiency data on existing and planned future thermal plants in Ghana as at end of 2023 is presented in Table 2. In all, there are 17 existing thermal plants. There is also an agreement in place for a 370 MW and 350 MW thermal plants to come on stream by 2026 (Abbey, 2023). These two are thus included in the model as future plants and enforced to be available for generation by 2026. The capacity factor of thermal plants in Ghana tends to be very high per their usage rate and are therefore assumed to be 0.85 for all the thermal plants. The efficiencies of the thermal plants can also be found in Table 2 based on their heat rates in ECG (2023).

Table 2 does not include data on Ghana's hydroelectric plants since this is not the focus of the study. However, the role of hydroelectric plants must be accounted for in the case study since they form a major part of the Ghana's electricity system. Since the two hydro plants of Akosombo (1020 MW) and Kpong (160 MW) are located in close proximity to each other and with roughly similar capacity factor, they are lumped together and referred to as Hydro1 with capacity factor of 0.75 according to data in ECG (2023). The remaining hydro plant by name Bui (404 MW) is referred to in the case study as Hydro2 with a capacity factor of 0.31 according to data in ECG (2023).

Table 2: Data on Ghana's thermal power plants in 2023 as used in the model.

Thermal Power Plants	Model Name	Installed Capacity (MW)	Dependable Capacity (MW)	Thermal Efficiency	Variable Cost ($/MWh)	Capital Cost ($/MW)	Fixed O&M Cost ($/MW/yr.)
Existing							
Takoradi Power Company (TAPCO)	Plant 1	330	315	0.40	73	1201000	14,760
Takoradi International Company (TICO)	Plant 2	340	330	0.43	73	1201000	14,760
Tema Thermal 1 Power Plant (TT1PP)	Plant 3	110	100	0.30	210	785,000	7,330
Tema Thermal 2 Power Plant (TT2PP)	Plant 4	80	70	0.29	73	1201000	14,760
Kpone Thermal Power Plant (KTPP)	Plant 5	220	200	0.29	210	785,000	7,330
Ameri Plant (AMERI)	**Plant 6**	**250**	**230**	**0.30**	**73**	**785,000**	**7,330**
Cenit Energy Ltd (CENIT)	Plant 7	110	100	0.29	210	785,000	7,330
Sunon Asogli Power Plant 1 (SAPP1)	Plant 8	200	190	0.36	73	1221000	14,760
Sunon Asogli Power Plant 2 (SAPP2)	Plant 9	360	340	0.44	73	1201000	14,760
Karpowership (KARP)	Plant 10	470	450	0.40	73	1201000	14,760
Trojan	Plant 11	44	40	0.29	73	1201000	14,760
Amandi (Twin City)	Plant 12	210	201	0.44	73	1221000	14,760
AKSA	Plant 13	370	330	0.40	73	1201000	14,760
Cenpower	Plant 14	360	340	0.43	73	1201000	14,760
Early Power (EALP)	Plant 15	200	190	0.45	73	1221000	14,760
Genser (GENS)	Plant 16	181	158	0.30	73	1221000	14,760
Takoradi T3 (TICO 3)	Plant 17	132	120	0.4	73	1201000	14,760
Sub total (existing thermal)		3967	3704				

Table 2 Source: ECG (2024); ECG (2023), Abbey (2023); EIA (2022), Vaillancourt (2014).

Table 2 also presents the variable cost, capital, and fixed operations and maintenance cost for the respective plants for the year 2023.

Table 3: 2024 Projected Electricity Demand for demand centers in Ghana

Location	Centre	Demand (GWh)
Accra	Center 1	6824
Tema	Center 2	6071
Kumasi	Center 3	3107
Takoradi (Tadi)	Center 4	4328
Sunyani	Center 5	1055
Tamale	Center 6	855
Bolgatanga	Center 7	314
Wa	Center 8	203
Koforidua	Center 9	869
Ho	Center 10	701
Cape Coast	Center 11	1260
Aflao	Center 12	2178

Source: GridCo (2022)

4.2.2 Electricity Demand and Demand Centers

There are in all 65 bulk supply points in the Ghana electricity system. These were aggregated around major regional capital cities, the industrial enclave of Tema, and Aflao the border town with Togo through which Ghana sells electricity primarily to Togo and Benin. These together result in twelve demand centers as shown in Table 3. The location decision problem is run using demand projections for Ghana in GridCo (2022). This projection runs from 2022-2031. The projection is extended to cover 2032 and 2033 using the annual demand increase of approximately 6.8% for 2022-2031. Using this projection, the demand for the twelve demand centers is estimated based on their proportions with respect to the 2023 national demand. The projected electricity demand by the twelve demand centers for 2024 is presented in Table 3.

Table 4: Re-location Cost of existing thermal power plants

Plant	Cost ($,000,000)
Plant 1	76.4
Plant 2	78.7
Plant 3	25.5
Plant 4	18.5
Plant 5	50.9
Plant 6	57.9
Plant 7	25.5
Plant 8	46.3
Plant 9	83.3
Plant 10	108.8
Plant 11	10.2
Plant 12	48.6
Plant 13	85.6
Plant 14	83.3
Plant 15	46.3
Plant 16	41.9
Plant 17	30.5

Source: EPRI (2014); ECG (2021)

4.2.3 Sites and Re-location Cost of Plants

There are in all seven selected candidate sites at which both the existing and future thermal plants can be relocated/located. These include the industrial enclave of Tema, and the mining towns of Obuasi and Tarkwa. The remaining sites are Takoradi, Kumasi, Sunyani, and Tamale, representing the coastal, middle, upper middle, and northern belts of Ghana. The candidate sites were selected based on the major electricity load centers in Ghana as found in GridCo(2020). Accra was not included as a candidate site since it is very close to Tema. The case study places a focus on Kumasi, the area at which plant 6 is to be relocated from its original location of Takoradi.

Table 4 gives estimated relocation cost (in millions of US dollars) of the plants from their original location to the seven candidate sites.

The data on relocation cost was taken from EPRI (2014) for a similar study that intended to relocate a 799 MW natural gas combined circle plant from Barcelona, Spain, to Buenos Aires, Argentina at an estimated cost of approximately US$143 million on a bare-erected, overnight basis. This cost excluded shipping at US$7.5 million, engineering and construction management at US$15 million, and contingency cost of US$25 million. Though plant relocation, if any, will be carried out within Ghana (a distance far less than from Spain to Argentina), shipping cost is not based on only distance covered, but other factors such as weight, distance to loading point, loading, unloading, and returning, a quarter of the shipping cost from Spain to Argentina was charged for transportation within Ghana. The final relocation cost therefore amounted to approximately US$0.2314 million per Megawatt. As a comparison, the cost is US$0.2290 if shipping cost is assumed to be zero, thus underscoring the reasonableness of the estimated relocated cost. Using this and plant capacity in Table 2 resulted in the total relocation cost as presented in Table 4. Note that the relocation cost is zero when a plant is not to be relocated.

4.2.4 Distance between Fuel Depots and Candidate sites

The distance between the two depots and the sites where the plants are located and where future plants will be located are shown in Table 5. These were determined based on Google map estimates. The two fuel depots are in Tema (a port city and an industrial enclave) and Atuabo where Ghana's gas processing plant is located. Note that Depot 1 is located at Site 1 whereas Depot 2 is located very close to Site 2 and Site 3. This data is important in accounting for the cost of transporting fuel from the depots to the sites where plants are located.

Table 5: Distance between fuel depots and candidate sites where thermal plants are to be located.

	Distance (km)						
Site	Tema	Tadi	Tarkwa	Kumasi	Obuasi	Sunyani	Tamale
Model Name	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7
Depot 1 (Tema)	0	253	334	275	299	396	598
Depot 2 (Atuabo)	252	98.7	85.3	287	205	397	676

Source: Google map

Table 6: Transmission distance (in km) between Thermal plant's candidate site and Demand Center

	Distance (km)											
	Centre 1	Centre 2	Centre 3	Centre 4	Centre 5	Centre 6	Centre 7	Centre 8	Centre 9	Centre 10	Centre 11	Centre 12
Site 1	30	0	275	252	396	599	743	735	101	163	174	157
Site 2	227	253	288	0	410	665	827	738	292	382	82	409
Site 3	308	334	204	85.3	310	579	741	664	379	463	163	491
Site 4	248	275	0	287	124	378	539	449	192	333	209	432
Site 5	227	299	59.4	205	180	434	596	507	234	375	175	410
Site 6	370	396	123	397	0	319	481	354	313	454	331	544
Site 7	651	598	390	676	328	0	163	305	595	496	597	600
Hydro1	**102**	**72**	**273**	**318**	**358**	**492**	**654**	**717**	**62**	**74**	**233**	**168**
Hydro2	**461**	**462**	**236**	**504**	**133**	**267**	**429**	**285**	**404**	**524**	**440**	**600**

Source: Google map

4.2.5 Distance (in km) between location of power plants and demand centers

The distance between the sites hosting the power plants and the demand centers is given in Table 6, where the location name is the same as the plant name for the hydro plants. Like the distance between depots and sites in Table 5, the data in Table 6 is important in accounting for the cost of transmitting electricity to the demand centers as well as losses during transmission.

4.2.6 Transmission Losses

From the data in the 2024 Ghana Energy Statistics, the average transmission losses from 2000-2023 is 4.06% of the total electricity transmitted. Per data from ETSAP (2014), there is approximately 7% loss over 1000km for an HVAC line. This translates to an average transmission loss of 0.007% per km. From Table 6, the average distance between candidate sites and demand centers is approximately 350km. By ESTAP (2014), this will amount to an average loss of 2.45% for an HVAC line which is extremely low when compared to the 4% average loss of Ghana over an average transmission distance of 350 km. Therefore, the percentage transmission loss per kilometer is set to 0.01% for the case study.

4.2.7 Transmission Service Charge

According to PURC (2023), the transmission tariff in the second quarter of 2023 in Ghana was GHp8.6647/kWh. With an exchange rate of GHC11.388 to a US$1 in June 2023, this amount is equivalent to US$0.00761/kWh or US$7.61/MWh. With an average distance of 350km from the plants to the demand centers, this translates to US$0.0217/MWh/km

4.2.8 Fuel Transportation Cost

According to Molnar (2022), the tariff rate for transporting natural gas through a pipeline range from a low of $0.5/mmbtu/1000 km and a high of

\$1/mmbtu/1000 km. This research uses the higher value of \$1/mmbtu/1000 km given that costs tend to be higher in developing countries such as Ghana, and to ensure that a decision to relocate a plant far away from a depot (and transport fuel to it) when made is not in doubt.

4.2.9 Assumptions

It is assumed that there will be only one relocation/location to be carried out per plant within the 10-year planning period. This assumption is made to ensure that plants are not subjected to relocation each period, a situation that will be impractical in the real world. If this is not the case, then Equation (2) can be expanded to accommodate such flexibility. Also, the plant GENSER at Site 3 is primarily for supporting mining operations and therefore not subjected to relocation.

The problem was programmed using the General Algebraic Modeling System (GAMS) optimization software package and solved using the ILOG CPLEX 12.6.0.0 solver.

5.0 Results

5.1 Location of Existing Thermal Plants

The results of the recommended locations within the ten-year period 2024-2033 for the existing and future thermal plants in the Ghanaian electricity system are presented in column 4 of Table 7a, and Table 7b respectively. Column 3 of Table 7a gives the current[1] location of the existing thermal plants in the Ghanaian electricity system. These are Tema (Site 1), Takoradi (Site 2), and Tarkwa (Site 3). In all, the model recommends relocating only one of the existing thermal plants, which is Plant 17 from Site 2 to Site 6. The remaining plants are not subject to relocation, implying that their current locations are appropriate when considering the model's constraints. Plant 6 (Ameri) which is the subject of contention between the Government of Ghana (GOG) and some civil society organizations, think-tanks, and the opposition political party is not recommended to be relocated from Site 2. Currently, Plant 6 has been relocated to Site 4 (Kumasi) as was planned by the GOG. Thus, the model's recommendation of keeping Plant 6 at Site 2 does not agree with the GOG's choice of Site 4. However, from Table 5 and Table 6, it can be deduced that Site 4 (also Center 3) and Site 6 (also Center 5) are just 124km apart. In addition, Site 6 located in the middle of the country is closer to the upper half of the country than Site 4. Thus, the model's relocation of Plant 17 to Site 6 not only goes to support the GOG's motive but suggest that the GOG carries out the relocation even further away from Depot 2 than planned. Though Plant 17 (132 MW) is smaller compared to Plant 6 (250 MW), the difference is made up with new thermal plants as explained in the next subsection. Given that Site 6 is far away from Depot 2 than Site 4, the foregoing analysis suggests that for demand centers that are far away from the fuel depots along the coast, their electricity demands should be met with plants sited closer to them than with electricity transmitted over long distances from the coast. Table 7a also presents information on the demand centers to be served by the plants after the relocation exercise. As can be seen, those existing plants not subject to relocation are dedicated to serving mainly the demand centers of 1, 2, 4, and 11 which are either located along or closer to the coastal belt of Ghana.

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[1] This is before the government relocated Plant 6 to Site 4

Table 7a: Existing and recommended location of thermal plants in the Ghanaian electricity system from 2024 to 2033. Also included are the demand centers to be served by the power plants.

Plant Name	Plant Number	Current location	Recommended Location	Centers served
TAPCO T1	Plant 1	Site 2	Site 2	1, 4, 11
TICO T2	Plant 2	Site 2	Site 2	1, 4,11
TT1PP	Plant 3	Site 1	Site 1	1, 2
TT2PP	Plant 4	Site 1	Site 1	1, 2
KTPP	Plant 5	Site 1	Site 1	1, 2
AMERI	Plant 6	Site 2	Site 2	1,3, 4,11
CENIT	Plant 7	Site 1	Site 1	1, 2
SAPP1	Plant 8	Site 1	Site 1	1, 2
SAPP2	Plant 9	Site 1	Site 1	1, 2
KARPOWER	Plant 10	Site 2	Site 2	1, 3, 4
TROJAN	Plant 11	Site 1	Site 1	1, 2
AMANDI	Plant 12	Site 2	Site 2	1, 3, 4, 11
AKSA	Plant 13	Site 1	Site 1	1, 2
CENPOWER	Plant 14	Site 1	Site 1	1, 2
EARLY POWER	Plant 15	Site 1	Site 1	1, 2
GENSER	Plant 16	Site 3	Site 3	3, 4, 11
TAKORADI T3	Plant 17	Site 2	Site 6	5
Hydro1			N/A	2,3,5,6,9,10,12
Hydro2			N/A	5,6,7,8

The exception is Center 3 (Kumasi) which is located in the middle of the country. The demand centers located in the middle belt and up north of the country (i.e., centers 3, 5, 6, 7, and 8) are to be served primarily with the Hydro2 located in the north of the country and with future thermal plants. This indirectly implies that the Ghanaian system should prioritize siting thermal plants closer to demand centers than fuel depot's locations. The centers served based on the model's output are in line with current plant dispatch operations of the Ghanaian electricity system.

5.2 Location of Future Thermal Plants

The results of the recommended locations for the ten-year period 2024-2033 for the future thermal plants in the Ghanaian electricity system are presented in Table 7b. The numbers in bracket alongside the name of the plants indicates the number of such plant types recommended at a particular site. In all, a combine circle gas turbine is preferred over an open-circle gas turbine.

Three CCGT2 plants of 370 MW capacity for a total of 1110 MW are to be located at Site 1, whereas one CCGT3 of 450 MW is to be located at Site 4 by 2026. Another CCGT1 plant of 300 MW capacity is recommended to be sited at Site 7 (Tamale) which is further up north of the country by 2026. Note that these sites are selected for the location of future plants primarily due to growing demand from centers around them than for their proximity to fuel depots. This can be inferred from the recommendation to site a CCGT3 and a CCGT1 respectively at Site 4 (Kumasi), and Site 7 (Tamale) which are far away from the fuel depots but closer to the middle and northern belt of Ghana. The result in Table 7b also indicates that for the next 10-year period, no thermal plant should be located at Site 2 (Takoradi) which happens to be very close to fuel depot 2. These together thus reinforces the earlier argument that for the Ghanaian electricity system, siting thermal plants closer to the demand centers appears beneficial to siting them closer to the fuel depot locations. Were this not the case, only Site 1 and Site 2 would have been recommended for hosting the future thermal plants since these locations are home to a fuel depot. From Table 7b and given the capacity of CCGT1 (300 MW), CCGT2 (370 MW) and CCGT3 (450 MW), the total new capacity needed to meet projected demand for the Ghanaian electricity system is 1860 MW over the 10-year period or roughly 186 MW annually. This is in tandem with projections in GridCo (2022). Currently, the GOG has signed an agreement to build two new thermal plants; a 350 MW and a 370 MW (for a total of 720 MW) Combine Circle Gas Turbine plants by 2026 Abbey (2023). This agrees with the recommendations in Table 7b of a CCGT3 (450 MW) plant at Site 4 and another CCGT1(300 MW) plant at Site 1 for a total capacity of 750 MW by 2026.

Table 7b: Number of new thermal plant types, their location, and at which year to bring on board the Ghanaian electricity system.

	Plant Location		
Year	*Site 1*	*Site 4*	*Site 7*
2026		CCGT3(1)	CCGT1 (1)
2031	CCGT2(1)		
2032	CCGT2 (1)		
2033	CCGT2(1)		

5.3 Operational Cost Impact of Thermal Plant Relocation

This section looks at the benefit to be attained when comparing the status quo, the GOG's relocation plan, and the model's recommended relocations/locations. Since the model was designed to ensure that electricity demand at all centers is met, the analysis will focus on only the total cost of electricity supply over the 10-year period.

5.3.1 Total Cost: Model versus Status Quo

The objective function value based on the model's recommendations as found in column 4 of Table 7a is US$20.481 billion. The model was also run under the status quo (when the existing locations in column 3 of Table 7a is followed) and resulted in an objective function value of US$20.493 billion. This translates to a present value savings of approximately US$12 million over the 10-year period even after accounting for the relocation cost. This savings is equivalent to an amount of US$1.63 million annually at an interest rate of 6% per annum. This means the suggested relocations by the model leads to less cost (about 0.06%) compared to maintaining the thermal plants at their current locations. This also supports the earlier assertion for the Ghanaian electricity system to site thermal plants closer to demand centers and transport the needed fuel to them than to just site them along the coast because of their proximity to the fuel depots.

5.3.2 Total Cost: Model versus GOG's Relocation Decision

The model was run under the GOG's decision of relocating the Ameri power plant (Plant 6) to Site 4 (Kumasi) to understand the extent of the benefit, if any of the GOG's decision. The objective function resulted in a value of US$20.504 billion over the 10-year period resulting in an extra cost of US$23 million (or US$3.12 million annually at an interest rate of 6% per annum) when compared to the model's recommendation. This also implies the suggested relocations by the model leads to less cost (about 0.1%) than the GOG's relocation decision.

5.3.3 Total Cost: GOG's versus Status Quo

From section 5.3.1 and 5.3.2, the total cost of electricity provision for the 10-year period is US$11 million more under the GOG's decision than under the status quo. At an interest rate of 6% per annum, this translates to an extra cost of approximately US$1.5 million annually. Thus, based on the costs and factors considered in this case study, the GOG's decision is slightly more costly (about 0.06%) than the case of maintaining Plant 6 at Site 2. Note that the model does not consider the cost saved due to improved electricity delivery as touted by the GOG for intending to move Plant 6 to Site 4. If the savings or benefits to be accrued from improvement in service delivery is comparable or exceeds US$1.5 million annually, then the GOG's decision is worthwhile. Otherwise, it is better the status quo is maintained.

Table 8: Comparison of relocation, transmission, transmission losses, and fuel transportation costs for the three decisions of maintaining the status quo, going by the GOG's decision, and the recommendation from the model

	Cost (US$ million)		
Cost Type	*Model*	*GOG*	*Status Quo*
Relocation	30.547	57.854	0
Transmission	356	341	393
Transmission losses	49.245	46.724	58.650
Fuel transportation	166	178	155
Total	601.812	623.678	606.920

Table 8 breaks down the various cost related to relocation, transmission, transmission losses and fuel transportation. This gives an insight into the trade-off made by each of the model as to relocate a plant closer to demand centers that are far away from the two fuel depots. Both the model's recommendation and the GOG's decision leads to transmission and transmission losses costs that are less than that of the status quo. This is because of the relocation that shortens the transmission distance, and therefore lesser transmission related costs. However, the opposite is true for the fuel transportation cost. This cost increases by virtue of relocating plants away from the fuel depots which is more under the GOG than under the model or status quo. Comparing the costs under the model and the GOG, it can be inferred that the model's choice of relocating Plant 17 to Site 6 instead of the GOG's decision of relocating Plant 6 to Site 4 is strategic. This is because, whiles the decision will leads to higher transmission related costs, it will compensate this with a lower fuel transportation cost. This illustrates the trade-off underlying the relocation problem. Note that the costs in Table 8 includes those from future thermal plants. Also, since the status quo does not involve any relocation, there is therefore no cost incurred on relocation.

6.0 Conclusion

This paper presented a locational decision model for assessing the relocation of existing thermal plants and the siting of future ones with an objective to reduce cost of electricity supply. The model is motivated in part by the decision of the government of Ghana to relocate a thermal plant which led to considerable debate among Ghanaian politicians and energy policy think-tanks. Analysis of the results from applying the model to the government of Ghana's decision reveals that whiles cost of electricity supply will increase the additional cost is not significant when compared to the benefit thereof as touted by the government. Even better, a new relocation plan recommended by the model will lead to a reduction in electricity supply cost, indicating the usefulness of the model. Overall, in the case of the Ghanaian electricity system, it is better to have thermal plants sited closer to demand centers that are far away from fuel depot locations and transport fuel to power them. Doing so reduces cost attributed to transmission losses.

The paper contributes to literature on optimal location of resources in general, allowing for the consideration of important factors that are treated subjectively in other models such as MCDM models. Power plant location decisions are generally treated in the literature with MCDM. However, the ability of MCDM to consider important factors such as transmission cost, transmission losses, and fuel transportation cost is limited. Also, many Generation Expansion Planning studies if ever includes location, does so with a focus on future plants. This is perhaps one of the few studies to provide an optimization model for the relocation of existing thermal plants and the location of future ones. The inclusion of relocation of existing plants thus makes the model unique. In addition, the consideration of fuel depot location, and cost related to fuel transportation and transmission losses makes the model outputs more objective than the subjective ones generated based on MCDM approaches. The proposed model contributes to practice. In the case of the relocation decision by the government of Ghana, such a model could be used to provide further evidence of cost justification to quell the doubts of stakeholders.

A limitation of the developed model is that it assumes relocation of existing thermal plants take place at the beginning of the planning period. Future work should be able to expand on this to make it possible to determine the exact period an existing plant should be relocated given demand projections and other relevant factors. Future works could also consider the case where demand centers compete for electricity due to insufficient capacity. This will require considering the economic contribution of demand centers.

Funding: This work was supported by the University of Ghana Business School Research grant [grant number UGBS/RCC/2024-25/021].

REFERENCES

Abbey, E. E. (2023). 2 Power pacts to generate 750mw - Energy Minster. *Graphic Online.* November 10, 2023. https://www.graphic.com.gh/news/general-news/ghananews2-power-pacts-to-generate-750mw-energy-minster.html

ACEP (2022) *Cautionary note to the ministry of energy on the Ameri power plant. Available* at: https://citibusinessnews.com/wp-content/uploads/2022/08/PRESS-STATEMENT-CAUTIONARY-NOTE-TO-THE-MINISTRY-OF-ENERGY-ON-THE-AMERI-POWER-PLANT-.pdf (Accessed: 15th July, 2023)

Afful-Dadzie, A., Afful-Dadzie, E., Awudu, I., & Banuro, J. K. (2017). Power generation capacity planning under budget constraint in developing countries. Applied energy, 188, 71-82.

Azevêdo, V. W. B., Candeias, A. L. B., & Tiba, C. (2017). Location study of solar thermal power plant in the state of Pernambuco using geoprocessing technologies and multiple-criteria analysis. *Energies*, *10*(7), 1042.

Choudhary, D., & Shankar, R. (2012). An STEEP-fuzzy AHP-TOPSIS framework for evaluation and selection of thermal power plant location: A case study from India. *Energy*, *42*(1), 510-521.

Dapaah, E. (2022): GRIDCo heightens advocacy for relocation of AMERI plant to Kumasi. Citi Business News. September 28, 2022. https://citibusinessnews.com/2022/09/gridco-heightens-advocacy-for-relocation-of-ameri-plant-to-kumasi/#:~:text=The%20250%2DMegawatt%20(MW),the%20northern%20sector%20of%20Ghana

Duarte, A. E., Sarache, W. A., & Costa, Y. J. (2014). A facility-location model for biofuel plants: Applications in the Colombian context. *Energy*, 72, 476-483.

EIA (2022, March). Cost and Performance Characteristics of New Generating Technologies. Energy Information Administration, Annual Energy Outlook 2022.

Electric Power Research Institute (EPRI) (2014). *Gas Turbine Combined Cycle Relocation Study*. June 2014. Available at: https://www.epri.com/research/products/3002003656 (Accessed: 20th June, 2023)

Energy Commission, Ghana (ECG) (2024). National Energy Statistics Bulletin 2024. https://www.energycom.gov.gh/newsite/index.php/planning/energy-statistics#

Energy Commission, Ghana (ECG) (2023). *Integrated Power Sector Plan for Ghana* Available at: https://www.energycom.gov.gh/newsite/index.php/planning/ipsmp-data# (Accessed: 15th July, 2023)

GridCo (2022). Twenty Twenty-Two Electricity Supply Plan for the Ghana Power System. The Energy Commission, Ghana. https://gridcogh.com/wp-content/uploads/2022/07/2022-Electricity_Supply_Plan-1.pdf.

GridCo (2020). Twenty Twenty-Two Electricity Supply Plan for the Ghana Power System. The Energy Commission, Ghana. https://gridcogh.com/wp-content/uploads/2022/05/2020-Electricity-Supply-Plan.pdf

Gumussoy, A. D., Onen, V., & Yalpir, S. (2024). Combined use of BWM-TOPSIS methods in the selection of thermal power plant installation site in the Karapinar/Turkiye Region, at risk of sinkhole formation. *Environmental Monitoring and Assessment*, *196*(1), 1-23.

https://www.eia.gov/outlooks/aeo/assumptions/pdf/table_8.2.pdf/

Ilbahar, E., Kahraman, C., & Cebi, S. (2021). Location selection for waste-to-energy plants by using fuzzy linear programming. *Energy*, 234, 121189.

Kashawn, H., Solange, K., & Legena, H. (2022). Site selection of ocean thermal energy conversion (OTEC) plants for barbados. *Renewable Energy*, *201*, 60-69.

Molnar, G. (2022). Economics of gas transportation by pipeline and LNG. In *The Palgrave handbook of international energy economics* (pp. 23-57). Cham: Springer International Publishing. https://link.springer.com/chapter/10.1007/978-3-030-86884-0_2#Sec10

Public Utilities Regulatory Commission (PURC) (2023). *2023 First Quarter Natural Gas , Electricity & Water Tariff Decision*. Available at: https://www.purc.com.gh/attachment/237449-20230714080734.pdf (Accessed: 3rd August, 2023)

Ravindran, A., & Hanline, D. L. (1980). Optimal location of coal blending plants by mixed-integer programming. *AIIE Transactions*, 12(2), 179-185. https://doi.org/10.1080/05695558008974505.

Rentizelas, A. A., & Tatsiopoulos, I. P. (2010). Locating a bioenergy facility using a hybrid optimization method. *International Journal of Production Economics*, 123(1), 196-209.

Siefi, S., Karimi, H., Soffianian, A., & Pourmanafi, S. (2017). GIS-based multi criteria evaluation for thermal power plant site selection in Kahnuj County, SE Iran. *Civil Engineering Infrastructures Journal*, *50*(1), 179-189.

Sun, W., & Qin, M. (2015). Research on Thermal Power Plant Location Based on Rough Set and Interval-valued Fuzzy Number. In *2015 International Conference on Social Science, Education Management and Sports Education* (pp. 1263-1266). Atlantis Press.

Vaillancourt, K (2014). Electricity Transmission and Distribution. IEA ETSAP Technology Brief April, 2014. https://iea-etsap.org/E-TechDS/PDF/E12_el-t&d_KV_Apr2014_GSOK.pdf

Wang, T., & Xin, B.C. (2011). Thermal power plant sitting based on TOPSIS method. *Procedia Engineering*, *15*, 5384-5388.

World Bank (2024). World Bank Open Data, Ghana Data. https://data.worldbank.org

Xie, Y., Zhao, K., & Hemingway, S. (2010). Optimally locating biorefineries: a GIS-based mixed integer linear programming approach. 51st Annual Transportation Research Forum, Arlington, Virginia, March 11-13, 2010. https://ageconsearch.umn.edu/record/207234/?v=pdf

Zurek, K. (2022): Abandon expensive plan to relocate AMERI Plant to Kumasi - CSOs to Energy Ministry. Graphic Online. August 11, 2022. https://www.graphic.com.gh/news/general-news/abandon-expensive-plan-to-relocate-ameri-plant-to-kumasi-csos-to-energy-ministry.html