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Power generation capacity planning under budget constraint in developing countries

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HIGHLIGHTS

- A long term stochastic GEP model with budget constraint is developed.
- Model suitable for analyzing GEP problems in developing countries.
- Model determines optimal mix, size and timing of future generation capacity needs.
- A real case study of the Ghana GEP problem was employed.
- Insufficient budget leads to costly generation capacity expansion plans.

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ABSTRACT

This paper presents a novel multi-period stochastic optimization model for studying long-term power generation capacity planning in developing countries. A stylized model is developed to achieve three objectives: (1) to serve as a tool for determining optimal mix, size and timing of power generation types in the face of budget constraint, (2) to help decision makers appreciate the consequences of capacity expansion decisions on level of unserved electricity demand and its attendant impact on the national economy, and (3) to encourage the habit of periodic savings towards new generation capacity financing. The problem is modeled using a stochastic mixed-integer linear programming (MILP) technique under demand uncertainty. The effectiveness of the model, together with valuable insights derived from considering different levels of budget constraints are demonstrated using Ghana as a case study. The results indicate that at an annual savings equivalent to 0.75% of GDP, Ghana could finance the needed generation capacity to meet approximately 95% of its annual electricity demand between 2016 and 2035. Additionally, it is observed that as financial constraint becomes tighter, decisions on the mix of new generation capacities tend to be more costly compared to when sufficient funds are available.

1. Introduction

The provision of regular and sustainable supply of electricity sits at the heart of every country's quest at ensuring quality of life for its citizenry. For many developing countries, annual real per capita GDP growth is known to be strongly linked to levels of electricity consumption [1,2]. Thus a developing country's ability to provide constant and reliable electricity is crucial to its economic growth. Evidence of this statement abounds particularly in sub-Saharan Africa where deficiencies in the power sector regularly impact the region's economic growth and competitiveness [3]. To achieve constant and reliable power supply, developing countries need proper planning towards future capacity needs that takes into account obstacles that hinder the adoption of best practices in power generation capacity planning. One of such obstacles with significant impact is lack of financial capital. Most developing countries face a recurring challenge raising needed capital to finance new generation capacities [4]. The challenge posed by unavailability or insufficient financial capital stalls plans toward future generation capacity expansion. Unfortunately, realization of the inability to secure required financial capital to implement planned expansion often comes late. This scenario results in developing countries regularly scrambling for alternative solutions to prevent high levels of unserved demand [3,5–7]. In a bid to rescue the situation, many developing countries fall back on emergency

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power plans which often call for short-term leases of expensive power generators [3]. To avoid resorting to costly emergency plans, generation capacity expansion must first be determined based on guaranteed cash flows. Following this, plans could be made far in advance to cater for anticipated unserved demand. It is of this need that this paper proposes a capacity expansion model that explicitly takes into account financial constraint.

A common practice to meeting future electricity demand in most developing countries has been to include capacity investment needs as part of annual national budget. In such circumstance, it is important that long term generation capacity planning models take into account periodic budget constraints to ensure realistic and applicable generation mix plans. This approach will help to properly project levels of anticipated energy demand that cannot be met, and the resulting consequences on the national economy. When consequences on the economy are fully known, it would help inform the need to increase allocated budgetary allocation for investment in new generation capacities. It must be noted that lack of funds impact the selection and timing of new generation plants to the extent that, plants with lower capital investment but higher running costs may be preferred to those with higher investment but lower running costs. This happens because the downside to waiting to secure enough funds for capital intensive plants is higher cost to the economy as a result of increases in unserved demand. This issue can however be efficiently analyzed by the inclusion of periodic budget constraint in the capacity planning model. Another important issue in power planning is uncertainty in demand. Electricity demand, especially in developing countries is highly uncertain which makes capacity planning difficult [8]. This, therefore, calls for generation capacity planning models that are specifically designed to handle demand uncertainty.

The issues raised above are studied in this paper with a multi-period stochastic mixed-integer linear programming (MILP) model. The minimizing stochastic MILP model is developed to determine the optimal mix, size and timing of generation plants under uncertain demand over a long planning period taking into account periodic budget constraints. The stochastic MILP model is also formulated in a way that encourages the habit of periodic savings towards financing future capacity expansion needs. This recognizes that in some years the allocated budget might be better utilized when saved for future use. This practice would be akin to the concept of sinking fund where money is saved towards a future need.

Many scholarly works have been produced on electricity generation capacity planning using optimization techniques. A comprehensive review of optimization techniques for Generation Expansion Problems (GEP) can be found in [9,10]. To address issues of uncertainty, most notably demand and fuel price, majority of optimization techniques employed are stochastic in nature (see for instance [9,11]). Stochastic optimization models have been proven to provide superior performance than other techniques when uncertainties in model parameters exist [6,9,12,13]. Moreover, since GEP problems are typically considered over a long period of time, such models are also multi-period in nature, resulting in so-called multi-period stochastic optimization models. One of the early scholarly contributions that employed multi-period stochastic optimization to GEP under demand uncertainty are [12] and [14]. Similarly, [6] used a multi-period stochastic linear optimization model with uncertainties in future demand and fuel prices to determine the type and size of power plants to be constructed over an extended planning horizon. The paper showed that optimal solutions of such models are robust when the uncertain scenarios are reduced for model tractability. In [15], a stochastic multi-period MILP model was developed to analyze economies of scale in capacity expansion cost. The approach is similar to the cost-benefit analysis for examining the worthiness of an increase in budget allocation in this paper. A recent study in [16] considered a generation expansion problem using multi-period stochastic MILP model under a new scenario generation approach. The objective function included cost of unserved energy similar to what is used in this paper.

A number of authors have also used multi-period stochastic optimization models for real world applications. A recent study in [17] used a multi-period stochastic optimization model to analyze the GEP problem in China taking into account non-carbon external cost of different power generating technologies. The result indicated that China would need capital equivalent of 2% of its GDP to finance future power expansion plans from 2015 to 2035. A similar model was employed in [18] to study power planning options for China taking into consideration regional variations in availabilities of resources and inter-region power transmission line capacity. In [19], a multi-period stochastic optimization model was applied to determine the optimal generation technologies, size, and timing of future expansion plans for the Greek power system. A sensitivity analysis was also conducted to study the influence of major model parameters such as fuel cost. A similar study for the Greek power system was conducted in [20] with an addition of unit commitment constraints. The work in [21] applied a multi-period optimization framework for the optimal planning of China's power sector between 2010 and 2050 with a focus on mitigating carbon emissions. The analysis centered on the impact of different levels of carbon cap and carbon price on the optimal capacity expansion plans. Similarly, [22] examined power capacity expansion plans for the Brazilian power sector by incorporating environmental costs associated with the construction and operation of power plants into the stochastic optimization model. Also, in [23], a stochastic MILP model for a centralized GEP problem was developed and applied to the Greek power system. The work in [23] included a sensitivity analysis to evaluate the effect of factors such as fuel and carbon emission prices, as well as investment capital. Other real world applications using stochastic optimization techniques can also be found in [24–27].

While much research have been carried into building models for solving long-term capacity expansion problems, most papers assumed the availability of sufficient funds for financing new capacities. Few studies have considered capacity expansion problems under budget constraints - one of the commonest problems facing developing countries. In our related literature search, only [28,29] [considered budget constraints in a stochastic optimization model for capacity expansion problems. The two-stage stochastic optimization model in [28] was developed with the objective of maximizing profit for a service industry with limited budget. The paper incorporated uncertainty in future demand to determine the size, schedule, location and timing of capacity expansions through a Lagrangian relaxation approach.

The model in [29] comes closest to that proposed in this paper. However, like in [28], the work in [29] considers a two-stage problem. The work in [30] also considered a capacity expansion problem for electricity generation in developing countries under a budget constraint. However, the problem was modeled through a systems dynamics and simulation approach and also did not consider uncertainty in demand. More importantly, [28–30] did not consider the practical case of periodic budget constraint but rather a single budget over the entire planning period.

Many developing countries allocate a portion of their annual budget to investment in the power sector (including the building of new generation capacities to meet annual demand increases in electricity). Therefore, it is important that models with periodic budget constraints are developed to fit such practice. Periodic budget constraint is considered in [31]. However, the model is deterministic in nature and also does not allow for unused budget to be available in subsequent period. This paper therefore proposes a new long term stochastic GEP model for the analysis of capacity