Power Development Planning Models in East Africa

B.K. Kinyanjui[1], A.N. Gitau[2] and M. K. Mang'oli[3]*
[1]Kenya Power and Lighting Company Limited, Nairobi, Kenya
[2]University of Nairobi; Department of Environmental and Biosystems Engineering, Nairobi, Kenya
[3]University of Nairobi; Department of Electrical and Information Engineering, Nairobi, Kenya

ABSTRACT

Power system planning can be widely viewed as consisting of three main areas: demand forecasting, generation capacity expansion, and transmission expansion planning. Power planning involves the determination of an optimal or least-cost development plan to meet forecast demand. This article examines power development planning and expansion, and planning models used in East Africa. It focuses on the planning process in three countries, Kenya, Uganda, and Tanzania, which historically interrelate in their economic activities across various sectors. The article seeks to give insight into power development planning with regard to a regional perspective, modeling and simulation, and trends and practices. It also seeks to elucidate the challenges and opportunities of integrated generation expansion planning.

Key words: planning, generation, model, optimization, simulation, load forecast, transmission.

INTRODUCTION

Power development planning methodologies and approaches provide an area of interest in view of integrated system operations and expansion. Power development planning can be divided into demand fore-

---

*Corresponding author: gitauan@yahoo.co.uk OR ayub.gitau@uonbi.ac.ke
Mobile: +254-722878029

casting, generation expansion, and transmission development. Generation expansion planning has historically addressed the problems of identifying ideal technologies, expansion size, and the siting and timing of the construction of new plant capacity in an economic fashion and manner which ensures that installed capacity adequately meets projected demand (Angela *et al.*, 2001). Simulation is fundamental in most aspects of power expansion planning and operation, and it finds increasing relevance with increasing grid network integration.

Three countries, Kenya, Uganda, and Tanzania, have historically been identified as East Africa, but the membership has since been expanded to include Rwanda and Burundi, which have now formally joined the East African Community (EAC). The initial three states correlate in their socio-political and economic activities, including power trade and development planning. Their power grids are similar, with common transmission and distribution voltages and frequency. This is the case since their ownership evolved around a common utility, the East African Power and Lighting Company, established in 1922. The Kenyan and Ugandan power systems have been interconnected for over 50 years through a 132 kV double-circuit power line built in 1957. No additional transmission tie lines have since been constructed, despite the great intent portrayed through frequent regional consultations aimed at furthering cooperation. The slow progress in further integration is attributed to many factors, most prominently the collapse in 1977 of the original East African Community. Despite the crumbling of EAC and the political turmoil experienced in Uganda until 1985, the Kenya-Uganda tie line remained intact, and power exports to Kenya continued, oblivious to the circumstances.

The combined installed system capacity of the three states was 2,888 MW in 2007, with hydropower constituting 57% of the installed capacity. Uganda's medium-term development plan includes 559 MW- committed projects for the medium term (2015), of which 509 MW will be hydro and 50 MW thermal. Kenya plans to install an additional 980 MW in the same period, comprised of 7 % hydro, 21% geothermal, 16% wind, 33% thermal, 3% wind, and at least 200 MW of imports from neighboring countries. Tanzania's committed projects until 2015 include 358 MW hydro, 100 MW gas-fired, 200 MW coal, and 400 MW imports.

Planned interconnector projects in the region include the Arusha-Nairobi (Tanzania-Kenya) line, a second Kenya-Uganda interconnector, and a 1,200 km Ethiopia-Kenya HVDC line that is expected to spur power trading in the larger East African area. Figure 1.1 shows the general layout of the power network in the region. Studies (i.g., BKS Acres, 2004) indicate that further interconnection of the three countries would have multiple economic and operational benefits. The same applies to integrated power development planning and expansion, which can be designed to take advantage of the commonalities and diversities of the partner states. The resultant benefits from the synergy would further economic prosperity and strengthen the union. Thus, this article evaluates planning processes and potential modeling and simulation systems aimed at optimizing power utility in the region.

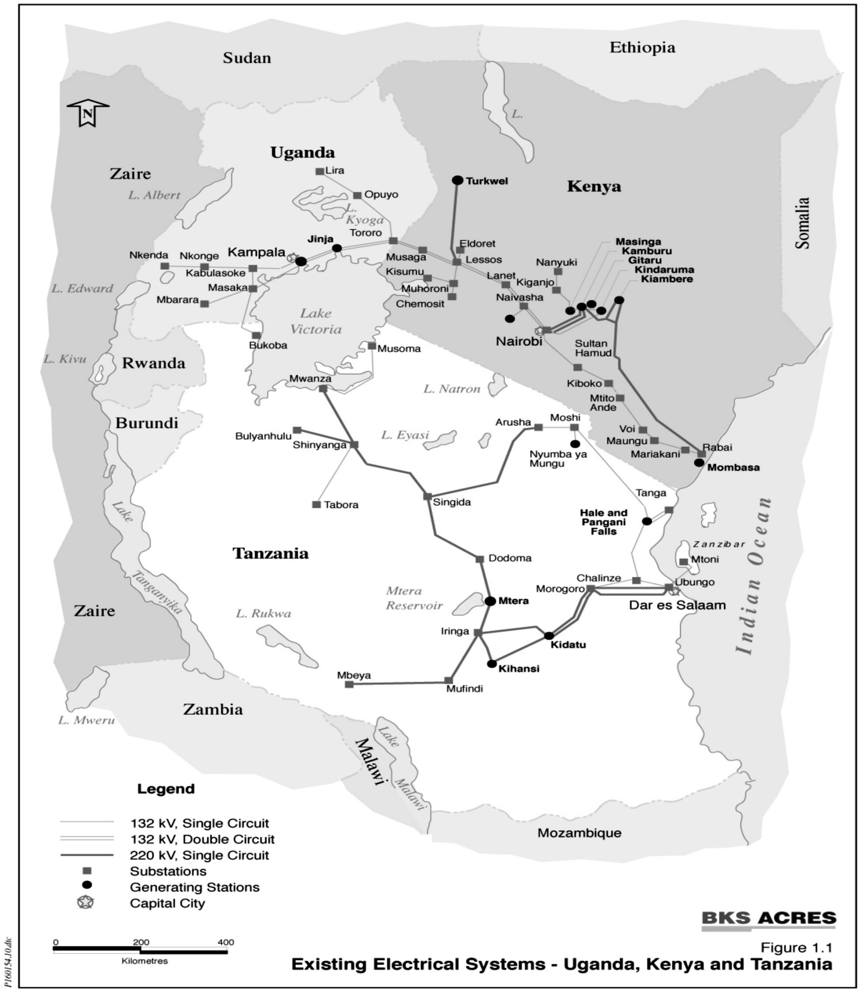

Figure 1. The General East African Grid Layout (Source: BKS Acres)

CAPACITY EXPANSION PLANNING

Generation expansion planning has historically addressed the problems of identifying ideal technologies, expansion size, and the siting and timing of the construction of new plant capacity in an economic fashion and manner which ensures that installed capacity adequately meets projected demand (Angela *et al.*, 2001). The aim is to determine the best plan to reliably meet projected demand at the least cost. Planning is about determination of an optimal development strategy. Many computer models/software have been developed for load projections and optimization of system operation and expansion. Four categories of models are usually used in capacity expansion planning: load forecasting models, hydropower system optimization models, capacity optimization models, and transmission system simulation. A number of models have been developed for diverse applications worldwide. Load forecasting models used in East Africa include the Model for Analysis of Energy Demand (MAED), the time series/econometric model, Eviews, and Message. Hydro-optimization models in use include VALORAGUA, ARSP, and Power Market Analyzer (PMA). For capacity expansion planning, the models used include WASP, GENSIM, Message, and PMA, while transmission modeling is primarily carried out using a common software, PSS/E.

Demand Forecasting

The models used for demand forecasting in East Africa include MAED, the time series model, E-views, and Message. Irrespective of any model used, accuracy of the input data used is paramount to derive the most realistic demand forecast so as to generate a plan that closely meets system requirements at the least cost. The demand forecast is therefore a very pertinent component of capacity expansion planning, since it influences the level and schedule of investment for the entire power system. Underestimates lead to shortfalls that call for institution of emergency remedial measures, while overestimates can result in unnecessary investments that eventually burden consumers.

Bharadwaj and Mehra (2001), in their review of several demand forecasting approaches and models, described demand forecasting as the science and art of specification, estimation, testing, and evaluation of models of economic processes that drive the demand for fuels. Forecasting methodologies for global use include the trend method, end-use method, econometric approach, and time series, as well as hybrid methods that apply combinations of more than one method.

The model of choice in the East African region is the time-series econometric hybrid model that involves regression analysis to determine the relationship of demand to key underlying factors, including GDP and tariff levels. The time-series method is used to establish relationships between electricity demand and other variables that have impact on the use of electricity.

The trend method is based on establishing how demand levels evolve over time based on historical consumption, enabling determination of growth factors projected into the future.

The end-use approach seeks to capture the influence of sources of energy and usage patterns and related growth and development on the overall electricity demand. End-use models for electricity demand establish the demand from the intensity of use in various sectors of the economy such as the residential, commercial, agriculture, and industrial sectors. The MAED model is a good example of an end-use model. It analyzes available sources of energy to determine the likely demand for electricity, based on competing factors. The model projects energy demand for all sectors of the economy for medium and long-term periods. MAED considers the demand by sector and captures the effects of the various sources of energy that may compete with electricity in a bottom-up approach or end-use method. Application of this model in the region has not been fully achieved, as it requires substantial data from across sectors, which to a certain extent inhibits its application in the region compared to countries with more advanced data capture and storage structures. Whereas the model enables prediction in systems that have fairly systematic variations, scenarios in African countries can change drastically such that the impact of one factor overrides others in contrast to the historical or projected trend. An example of such is a change of government and review policies that result in a shift of unpredictable trends.

Regression models find more application, as they use more of the readily available historical electricity data for establishment of trends and, therefore, projections.

Hydropower Reservoir Simulation

Modeling and simulation are integral activities in hydro-thermal system optimization and management. The problem of planning and managing multipurpose reservoir systems, most often stated as an optimal control problem, has been and continues to be a subject of extensive research work (Koutsoyiannis *et al.*, 2002). This can be attributed to the fact that reservoir systems are complex, as they involve many interrelated operations such as river inflow, abstractions, spillways, and hydropower applications. Other pertinent factors in a reservoir include mandatory (environmental) releases, recreational needs, and irrigation. River and reservoir systems are usually operated according to policies dictated by various decrees, agreements, and other formally recognized laws (Zagona *et al.*, 2001). Authentic data and information relating to hydropower reservoir systems are crucial for operation and prediction activities, which are core for optimal utilization of hydro resources.

In the East African region, two reservoir models, Acres Reservoir Simulation Package (ARSP) and VALORAGUA, have primarily been applied in generation expansion planning.

ARSP is a software model for simulating the operation of water resource systems, capable of simulating systems containing multiple reservoirs and multiple water uses. It is described as suitable for medium to long-term operational planning with resource systems having conflicting demands. Reservoir draw-down rule curves are used to develop a strategy for the operation of a reservoir or a group of reservoirs. The objective of analysis in simulations for specified system energy demands is to find the firm energy capability of a particular system configuration in all simulation runs. Energy production is measured in terms of the average power output over the time period. ARSP uses a network algorithm that solves a subset of generalized linear programming problems. Two key output parameters are desired—minimum energy production in all the time periods simulated and average energy production in all the time periods simulated.

The VALORAGUA model (name adopted from the Portuguese "value of water") can be used to enable optimization of operation of a hydrothermal electric system. The model is a microcomputer package software developed in FORTRAN, composed of several modules implemented to perform the management of a hydrothermal electric power system at a national level (or with interconnections to other countries or areas). Its application involves modeling of the hydro according to seasonal variations and optimizing the system operation while maximizing hydro output, with the objective of minimizing power system plant operation costs over one year, month-by-month, or week-by-week periods (REN, 2001). It establishes the optimal strategy of operation for a given power system by the use of the value of water concept (in energy terms) in each power station, for each time interval (i.e. month/week), and for each hydrological condition. For hydro power plants, the model takes into account that the water may have other uses in addition to the energy generation. The detailed analysis performed by the model, particularly for hydro power plants, enables determination of operational characteristics in order to incur a minimum of operational costs. The model supplies detailed information about technical, economical, and environmental behavior of the system and of each generation center, taking into consideration the randomness of hydrology. It also supplies a careful calculation of the economic dual variables, the marginal generation cost, and the marginal value of water for each hydroelectric plant.

Capacity Expansion Optimization

The Generation Simulation (GENSIM) package owned by Acres International of Canada has been in use for sometime in East Africa in the preparation of least-cost power development plans (KPLC, 2005). The package analyzes possible expansion plans using three modules, namely the GSPlan for capacity planning, the GSOper for operation of plants, and the GSEcon for economic analysis of the alternative plans. Planning data for modeling a power system include projected system demand and fuel costs, investment costs, and plant operational data. The planning module analyzes possible expansion plans under the set criteria of loss of load expectation (LOLE) and maximum expected unserved energy (EUE). The output of the GSPlan is a feasible generation expansion module and its associated plant maintenance schedule under critical drought conditions. The GSOper module uses the output of the GSPlan to calculate net energy output and fuel consumption per plant. The economic module, GSEcon, calculates the present worth cost (PWC) of each sequence based on capital cost, operational cost, and the cost of energy not served. The simulated sequence with the lowest PWC is considered the least-cost plan. One important limitation of this model is its inability to carry out optimization of several configurations, instead optimizing the limited combinations assembled and presented by the user. It therefore relies largely on the planners' experience and judgment.

The Wien Automatic Simulation Planning Package (WASP) software is gaining preference in regional capacity expansion planning and is expected to be the main planning tool in the near future. The load forecast and outputs of the VALORAGUA reservoir simulation model are utilized by WASP in determination of the least-cost plan (described as the optimal solution.) WASP is an optimization program that determines the generation expansion plan to meet projected demand at minimum cost, subject to input constraints. WASP evaluates many combinations of candidate generation projects to obtain a least-cost expansion plan for a given period. WASP simulation outputs include:

- Alternative expansion plans and their net present value (NPV) costs
- Annual financing requirements
- Summary reports

A strong feature in the software is its ability to configure possible generation expansion plans and use dynamic programming to evaluate them while allowing consideration of various constraints such as reliability, fuel usage, generation, and emissions. Equation [1] shows the objective function of the WASP simulation software, utilized in determining the optimal plan from presented candidate generation sources.

$$B_j = \sum_{t=1}^{T} \left[I_{j,t} - S_{j,t} + L_{j,t} + E_{f,t} + M_{j,t} + O_{j,t} \right] \qquad [1]$$

where:

Bj = The objective function attached to the expansion plan j
t = The time in years (1, 2, ... , T)
I = Capital investment costs
S = Salvage value of investment costs
F = Fuel costs
L = Fuel inventory costs
M = Non-fuel operation and maintenance costs
O = Cost of the energy not served
(Source: IAEA, WASP-IV User's Manual)

The WASP optimal expansion plan is defined by:

Minimum Bj among all j

The model utilizes: (1) a probabilistic estimation of system production costs, unserved energy costs, and reliability; (2) a linear programming technique for determining optimal dispatch policy satisfying exogenous constraints on environmental emissions, fuel availability, and electricity generation by some plants; and (3) the dynamic programming method for optimizing the cost of alternative system expansion policies. The model can be utilized to find an optimal solution for a power-generating system over a period of up to thirty years, within constraints given by the planner. The optimum is evaluated in terms of minimum, discounted total costs. Each possible sequence of power units added to the system expansion plan that meets the constraints is evaluated by means of a cost function or the objective function presented in Equation 1. The optimal expansion plan is the one that returns minimum Bj among all j. Generation by each plant for each period of the year is estimated based on an optimal dispatch policy, which is, in turn, dependent on availability of plants/units, maintenance requirements, spinning reserve requirements, and any other exogenous constraints imposed by the user.

Capacity Expansion in the Region

Planning activities carried out in the three countries until the mid 80s primarily focused on meeting demand using domestic sources. Interconnection between Kenya and Tanzania was considered sensitive (Acres, 1990). Table 1 shows the historical growth in installed capacity (MW) for the countries in the last two decades. The sequence of proposed capacity addition in a least-cost power development plan is usually derived based on identified pertinent or underlying factors that inherently have varying degrees of uncertainty. Table 1 indicates that the total installed capacity

	1987			**1997**			**2007**		
	Tanzania	Kenya	Uganda	Tanzania	Kenya	Uganda	Tanzania	Kenya	Uganda
Hydro	331	349	160	331	599	180	561	677	394
Geothermal	0	45	0	0	45	0	0	128	0
Thermal/GT	0	164	14	214	132	14	647	381	100
Coal	0	0	0	0	0	0	0	0	0
Import	0	30	0	0	30	0	0	~0	~0
Total	**331**	**588**	**174**	**545**	**806**	**194**	**1,208**	**1,186**	**494**

Table 1. Interconnected System Installed Capacity in 1987, 1997 and 2007 in MW

grew by 41% between 1987 and 1997 and that the growth doubled in the last decade, but Uganda exports to Kenya were reduced from 30 MW to the current non-firm exchanges. The 1990 Kenya-Tanzania interconnector study indicated that the project was feasible and could provide energy benefits, investment benefits, and operational benefits as required.

Interconnections through 132 kV or 220 kV were initially recommended, as well as turbine governor settings adjustments and a harmonized governor-setting policy and installation of shunt reactors in long transmission lines for stable synchronous operation. Recent studies favor installation of a 400 kV interconnector. Simulations revealed that banking exchanges could be increased with reservoir operations coordinated between the two countries. The study recommended an Arusha-Nairobi interconnection and deferment of a planned coal plant in Mombasa, Kenya, as well as a delay in construction of a second Mombasa-Nairobi transmission line in favor of regional integration and increased hydro output from planned Tanzanian projects. The regional power master plan prepared in 2004 confirmed the benefits of further system integration in East Africa. The economic benefits envisaged include hydro complementarities in which reservoir drawdown can be coordinated so as to conserve storage in one country to take advantage of conditions in another so as to avoid spillage. Other benefits are load diversity, system operation, and displacement of expensive thermal generation though exchange of surplus energy. Pooled development is the modern trend, as it would enable reduction in capital expenditure by maximizing all available capacity. Revenues from power trade can be channeled to further infrastructure development projects to increase access to electricity. The Southern Africa Power Pool provides a showcase of successful regional optimization and mobilization of resources for mutual benefit.

A larger regional project named the Zambia-Tanzania-Kenya Interconnector Project (ZTK) was proposed to enable power trade between Eastern African countries and the Southern African Power Pool (SAPP), which previously had surplus capacity of cheaper power. The 2004 regional power master plan, however, found the ZTK project more expensive, as it required construction of long high-voltage transmission lines all the way from Zambia. The common desire to partner in power development in the region has nonetheless remained a living idea and a ubiquitous agenda in regional forums, but a great challenge. Factors which contribute to delays in further interconnection include the facts that power generation and transmission projects are capital intensive and that most countries at present have inadequate generation capacity, curtailing opportunities for the power trade that is a key incentive for interconnector projects.

Although regional-level projects have not achieved sufficient momentum in the East, sizeable national projects ironically continue to be implemented as each state takes on the responsibility of supplying national demand. Some generation and transmission projects that cost more than proposed interconnector projects attract financing ahead of the common projects. The growth in demand is, however, outstripping supply, and currently the three countries have contracted expensive emergency generators to alleviate substantial power shortfalls that have been aggravated by the now frequent droughts and unpredictable weather patterns in the changing global climate. The benefits expected from regional projects have been studied and are enormous and justifiable; the need to devise intervention measures to overcome impediments to the desired progress of the common projects is imperative. Strategies that can be applied include policy review, increased high-level sensitization, budget allocation, project packaging, and the signing of irrevocable commitments. Declarations should be made on how to attain firm implementation commitments and schedules, as well as the institution of penalties for avoidable delays. An encouraging example of a successful outcome of regional cooperation in the power sub-sector is cross-border electrification in the EAC, where several border towns have recently been electrified from the nearest grid. A regional strategy on scaling-up access to modern energy services, prepared with assistance from the UNDP and GTZ and aiming at facilitating achievement of the Millennium Development Goals (MDG) and poverty reduction (by developing MDG-based energy access investments in the framework of high-impact, low-cost scalable options) is expected to contribute further gains in the wider energy sector in the future. Another key study expected to have positive impacts in the region has been recently been concluded under the Nile Basin Initiative, targeting power projects of interest to at least two countries in the Nile equatorial region.

CONCLUSION

Demand for electricity is expanding with the economic growth and rural development in East Africa, along with the need for wider data capture and modeling emerging more prominently in planning. As the countries strive to raise combined electrification from the current level of below 20%, against the background of diminishing supplies of traditional biomass energy sources and escalating crude oil and coal prices, there is a need to review energy supply strategies and optimize existing sources and new investments. To achieve this objective, regional integration must be enhanced to derive the envisaged benefits demonstrated by various studies. Translation of plans to projects would move power planning a notch higher and open new windows of opportunity to tame elusive integrated resource planning in the power sector. The generation potential has been highlighted, as well as possible avenues for synergy and optimal operation and expansion of the three systems. Power planning is moving towards end-use forecasting models and optimization models designed for hydro-thermal systems. Consensus and harmonization of planning tools and methodologies would have significant advantages towards the desired level of coordinated planning and development. The enormous and justifiable benefits expected from regional projects require intervention measures to overcome impediments. Strategies that can be applied include policy review, increased high-level sensitization, increased budget allocation, project packaging, and the formulation of irrevocable mechanisms for implementation of agreed-on projects.

References

Acres International (1990). *Kenya-Tanzania Interconnector Transmission Line*. Acres International Limited, Niagara Falls, Canada, 1990.

Angela S. Chuang, Felix Wu and Pravin V. (2001). *A Game-Theoretic Model for Generation Expansion Planning: Problem Formulation and Numerical Comparisons.* Power Systems, IEEE Transactions, Volume 16, Issue 4; November 2001 Pages 885 - 891.

Bharadwaj Aarti G. and Meeta K. M. (2001). *Demand Forecasting for Electricity: the Indian experience*. In Sarkar S. K. and Deb Kaushik (Eds); Regulation in Infrastructure Services: progress and the Way Forward". TERI, 2001. ISBN: 8185419884.

BKS Acres International (2004). *East African Power Master Plan Study*. BKS Acres International Limited". Niagara Falls, Canada.

IAEA, International Atomic Energy Agency (2000). *Wien Automatic WASP User's Manual-version WASP-IV*. IAEA Planning and Economic Studies Section, Vienna, Austria. IAEA Austria, 2000.

Koutsoyiannis D., Efstratiadis A. and Karavokiros G. (2002). *A Decision Support Tool for the Management of Multi-Reservoir Systems*. Journal of The American Water Resources Association Vol. 38, No. 4 American Water Resources Association, August 2002. Blackwell Publishing, Inc.

Kinyanjui, B.K. (2008). Optimization of power plant dispatch and capacity expansion in Kenya. Unpublished MSc. thesis. University of Nairobi; Kenya.

KPLC (2005). The Kenya Power and Lighting Company, *Least Cost Power Development Plan, 2006-2026*, Nairobi Kenya

REN-Rede Eléctrica Nacional S.A. (2001). *VALORAGUA for Windows: A Model for the Optimal Management of Electric Generating System*. REN-Rede Eléctrica Nacional S.A, 2001.

Zagona E. A., Fulp T. J, Shane R., Magee T. and Goranflo H. M. (2001). *A Generalized Tool for Complex Reservoir System Modeling*. Journal of The American Water Resources Association Vol. 37, No.4 American Water Resources Association August 2001. Blackwell Publishing, Inc.

ABOUT THE AUTHORS

B.K. Kinyanjui holds an M.S. degree in environmental engineering from the University of Nairobi and is an employee of Kenya Power and Lighting Company Limited, P.O. Box 30099-0100, Nairobi, Kenya. He is a systems engineer with over 12 years work experience and 5 years research experience in energy-related activities.

e-mail: bkinyanjui@kplc.co.ke

Dr. Ayub N. Gitau holds a Ph.D. in agricultural engineering from the University of Nairobi and is a senior lecturer in the University of Nairobi Department of Environmental and Biosystems Engineering, P.O. Box 30197-0100, Nairobi, Kenya. He has over 15 years teaching and research experience in the area of energy, power, and machinery engineering.

e-mail: gitauan@yahoo.co.uk

Dr. M.K. Mang'oli holds a Ph.D. in electrical engineering from the University of Nairobi and is a senior lecturer in the University of Nairobi Department of Electrical and Information Engineering, P.O. Box 30197-0100, Nairobi, Kenya. He has over 20 years teaching and research experience in the area of power planning and systems engineering.

e-mail mkmangoli@yahoo.com