Developing an Integrated Energy Model for the Eastern African Power Pool (EAPP)

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***Abstract*— An energy model for EAPP is in development using PLEXOS® and currently includes hourly level demand and energy forecasts (2010-2038), existing grid connected generators, fuels, emissions and existing/planned inter-country interconnectors with their technical characteristics modelled accordingly. The developed energy model has been used for three case studies demonstrating the benefits of interconnection between EAPP nations, performance of optimal maintenance scheduling and an example of integrated gas-electric modelling in Tanzania. The use of an energy model of this nature empowers decision makers in utilities, regulatory bodies, government agencies as well as private industry to make informed, risk adjusted decisions on critical infrastructure requirements.**

Keywords—Energy model, EAPP, PLEXOS®, transmission, maintenance optimisation, gas-electric

I. Introduction

A. Establishment of the EAPP

The Eastern African Power Pool (EAPP) was established in 2005 by the signing of an Inter-Governmental Memorandum of Understanding between seven East African nations. These were complemented by an additional three nations from 2010-2012. The members of EAPP are shown in Table 1 [1].

With the EAPP's mission of interconnecting all East African member nations, significant investment in generation and transmission infrastructure is required to meet the high levels of electrical demand growth expected. Investment in this infrastructure requires complex decisions to be made as they relate to which generation and transmission infrastructure is technically and economically feasible whilst considering the global drive towards a low-carbon sustainable future. These complex decisions involve a number of considerations and parameters including the prevailing energy markets in each nation and regional trading in the EAPP.

B. Background

The Eastern Africa region is endowed with a wide range of energy resources including hydro, wind, solar, geothermal, gas and coal which if traded in the region could allow for significant economic benefits. Using an energy model based purely on public domain information and generally accepted industry practice, an energy model for the EAPP has been developed using PLEXOS® [2]. The developed model was then used for a number of case studies to demonstrate the value of the developed model.

Table 1 EAPP MEMBERSHIP (2013)

Entity	**Abbreviation**	**Country**
Régie de Production des Eaux et de l'Electricité	REGIDESO	Burundi
Société Nationale d'Electricité	SNEL	DR Congo
Egyptian Electricity Holding Company	EEHC	Egypt
Ethiopian Electric Power Corporation	EEPCo	Ethiopia
Kenya Electricity Generation Company	KenGen	Kenya
The Kenya Electricity Transmission Company	Ketraco	Kenya
Kenya Power and Lighting Company	KPLC	Kenya
General Electricity Company of Libya	GECOL	Libya
Electricity Water and Sanitation Agency	EWSA	Rwanda
National Electricity Corporation	NEC	Sudan
Tanzania Electric Supply Company Ltd.	TANESCO	Tanzania
Société International d'Electricité des Pays des Grands Lacs	SINELAC	DR Congo–Rwanda–Burundi
Uganda Electricity Transmission Company Limited	UETCL	Uganda

II. The Energy Model

The energy model has been developed utilising the mathematical programming and stochastic optimisation framework provided by PLEXOS® to develop a powerful energy model for the EAPP. The energy model draws on information and data contained in the EAPP Power System Master Plan and Grid Code Study [3] complemented by generally accepted industry assumptions and other select references [4], [5].

As it stands, the model is a regional level model focused on the electrical systems for each of the countries in the EAPP. Future work will include inter alia sufficiently detailed models of gas systems as well hydro reservoirs and waterways to allow for a fully integrated energy model of the EAPP.

The model developed thus far includes the following elements:

- 260 generators including hydro, Open Cycle gas Turbines (OCGTs), Closed Cycle Gas Turbines (CCGTs), combustion engines, boiler steam generators, wind turbines and parabolic trough Concentrated Solar Power (CSP) technologies. Technical characteristics modelled include number of units. maximum capacity, heat rates, fuels, variable operations & maintenance costs, firm annual energy (for hydro generators), minimum stable levels, minimum/maximum ramp rates, minimum up/down times, Forced Outage Rates (FORs), Unforced Outage Rates (UFOR) and Mean Time to Repair (MTTR).
- A range of fuels as required by generators (one fuel type per fuel to remove distortions created by subsidies within individual EAPP nations). Fuels modelled include bagasse, natural gas, geothermal steam, Heavy Fuel Oil (HFO), Light Fuel Oil (LFO), oil, peat and representative renewable fuels for energy offtake assessments (water, solar, wind)
- Carbon Dioxide (CO_2) emission intensity per fuel type.
- Historical and forecasted demand and energy profiles for each country at an hourly level of granularity. This takes into account the maximum demand and energy forecasts of each EAPP nation from 2010 up to 2038.
- Existing/committed and planned interconnectors in the EAPP (as of 2010). Technical characteristics modelled include maximum/minimum flow, line resistance, line reactance, FOR and MTTR.

A summary of the electrical supply statistics as modelled for EAPP is given in Table 2. As can be seen, there is a range of hydro to thermal generation capacity in each EAPP country. For example, Egypt has significantly more thermal generation capacity relative to hydro capacity, Kenya has a reasonably balanced portfolio while Uganda is a hydro dominated system. When including Egypt, the EAPP is dominated by thermal generation (77%) but does have reasonable hydro generation capacity (22%) with minimal renewables penetration thusfar. When excluding Egypt, the EAPP has an increased share of hydro generation capacity (37%) but is still dominated by thermal generation capacity (62%). Wind and solar renewables penetration is still quite minimal in the EAPP.

A summary of the electrical demand statistics as modelled for EAPP is given in Table 3. Egypt is the largest energy user in the EAPP followed by Libya, medium users (Ethiopia, Kenya, Sudan, Tanzania and Uganda) and small users (Burundi, DRC (Eastern) and Rwanda).

As can be seen in the existing EAPP interconnectors in Fig. 1, there is currently a low level of interconnectivity between EAPP nations. The existing interconnectors between DR Congo-Burundi-Rwanda are at 70 kV and 110 kV (part of SINELAC where generating capacity at Ruzizi is shared between the three nations). Other small 132 kV interconnections between Kenya-Uganda and Uganda-Tanzania allow for small amounts of energy to be traded. Larger interconnectors include the recently completed 220 kV Ethiopia-Sudan, 220 kV Ethiopia-Djibouti interconnectors as well as 220 kV Egypt-Libya interconnector.

As can be seen in Fig. 2, there are a number of planned interconnectors for the EAPP including:

- 220 kV projects (Uganda-Kenya, Tanzania-Burundi, Uganda-Rwanda Tanzania-Rwanda, Tanzania-Uganda)
- 400 kV projects (Tanzania-Kenya and Uganda Kenya)
- 500 kV Ethiopia-Sudan
- 500 kV and 600 kV HVDC projects between Egypt-Sudan and Ethiopia-Kenya respectively

These planned interconnectors will significantly boost the ability within EAPP to trade electricity as well as increase the interconnected power system reliability.

III. Selected Case Studies

A. EAPP transmission interconnection

The developed EAPP energy model is run for one year (2010) with the following hypothetical scenarios:

- No interconnection
- Existing interconnections
- Planned interconnectors

This will reveal the benefit to the EAPP of transmission interconnectivity by demonstrating the sharing of resources between nations with surpluses/deficits in generation capacity.

Energy is allowed to move freely along interconnectors with the only limitation being their maximum/minimum power-flow limits.

B. Optimal maintenance scheduling

The developed energy model is run using the Projected Assessment of System Adequacy (PASA) module in PLEXOS® for the 2010. PASA optimally schedules generation/transmission maintenance events in an attempt to equalize capacity reserves.

The output from PASA being the optimal generation/transmission maintenance schedules (amongst other outputs) can be used for subsequent phases of simulations e.g. medium term operations planning, short term unit commitment and dispatch.

C. Integrated gas-electric assessment: The Tanzania case

In order to demonstrate the envisaged integrated gas-electric model for EAPP, the offshore Songo-Songo gas field and ~200 km pipeline north to Dar es Salaam (Tanzania) was modelled as an example.

The gas processing capacity at Songo-Songo is rated at 110 MMcfd (~107 TJ/day) [6]. The main use for this natural gas is Gas-to-Power (GTP) in Dar es Salaam complemented by some industrial use [6].

Simulations are run for a typical month in 2010 assuming usage of the Songo-Songo gas by GTP in Dar es Salaam. A small amount of gas demand is assumed for industrial purposes. This simulation attempts to demonstrate the impact that gas supply constraints could have on the Tanzanian power system dispatch.

Fig. 1. EAPP existing interconnectors modelled (2011)[1]

Fig. 2. EAPP planned interconnectors modelled (2038)[1]

IV. Results and Analysis

A. EAPP transmission interconnection

The results in 0 reveal the benefits of transmission interconnection. The average wholesale energy cost with the existing interconnections in the EAPP is 18% lower than with no interconnections. With the hypothetical scenario of all planned interconnections in 2010, the average wholesale energy cost is 49% lower when compared to no interconnections. Thus, when comparing the existing interconnectors to the planned interconnectors scenario, a decrease in average wholesale energy costs of 38% is noted.

Utilization of existing and planned interconnectors varies but for 2010 is on average 36%. Maximum utilization is on the 220 kV Egypt-Libya interconnector (83%) while the lowest utilized interconnector is the 110 kV Rwanda-Eastern DRC interconnector (7%). For the hypothetical planned interconnectors in 2010, the average utilization is 19%. The maximum utilization is again the 220 kV Egypt-Libya interconnector (84%) while the lowest is the 132 kV Kenya-Uganda interconnector (1%) which is mostly due to the planned 220 kV and 400 kV Kenya-Uganda interconnectors being utilized first (where the power would prefer to flow as a result of decreased losses).

Examples of the interconnector flows for the 2010 calendar year are given in Fig. 3 and Fig. 4 for the Egypt-:Libya and Rwanda-Eastern DRC interconnectors respectively. The forced outages on the interconnectors (as a result of the FOR

[1] End-points and line routes are only geographically represented between countries (locations are not geographically accurate)

and MTTR defined in the model) can be seen by the import/export limit notches for the brief outage period.

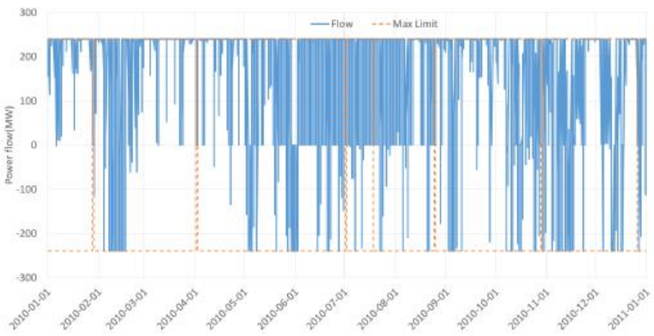

Fig. 3. Egypt-Libya power flow (2010 existing interconnectors scenario)

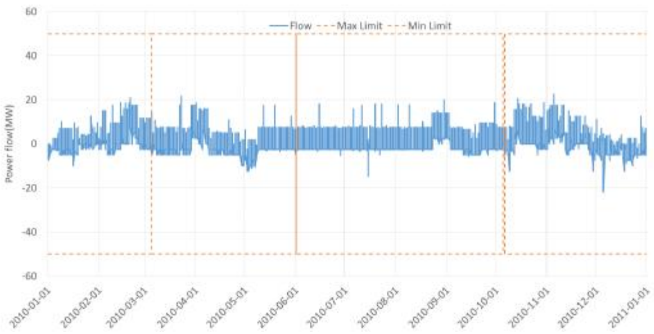

Fig. 4. Rwanda-Eastern DRC power flow (2010 existing interconnectors scenario)

B. *Optimal maintenance scheduling*

For brevity, only the maintenance optimsation performed for generators in Kenya is shown in Fig. 8. In this case, the PASA optimization is performed for the entire EAPP as one region (as opposed to each individual country). As can be seen, the maintenance in Kenya is performed in the out of peak season for EAPP (June-July). The forced outages cannot be controlled as these occur randomly throughout the year.

An example of the maintenance and forced outage of the bagasse fired Kakira steam turbine generator (Uganda) is shown in Fig. 5. As can be seen, maintenance occurs during the off-peak periods while forced outages occur randomly throughout the year based on the defined maintenance rate, FOR and MTTR.

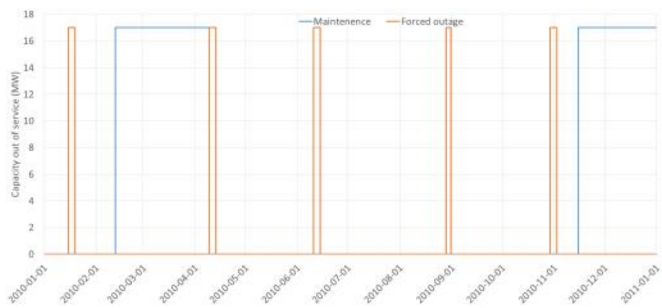

Fig. 5. Maintenance and forced outages for Kakira bagasse steam generator

C. *Integrated gas-electric assessment: The Tanzania case*

The gas processing capacity of ~107 TJ/day is used to show the effect of this constraint on the energy model. Fig. 6 shows the fuel offtake for the GTP plants in Dar es Salaam with assumed industrial gas demand (24 TJ/day) for January 2010. As can be seen, the effect of the gas supply constraint is that the combined GTP plants and industrial gas demand are constrained when compared to the case with no gas supply constraint. In this case, it is interesting to note that an additional 30 TJ/day of gas supply capacity (~27%) would allow for GTP fuel requirements and industrial gas demand to be met.

An example dispatch week (1-7 January 2010) is shown in Fig. 7 to demonstrate the effect that the gas supply constraint has on the Tanzania power system dispatch. The decrease in generation dispatch from the GTP plants is ~10-20%.

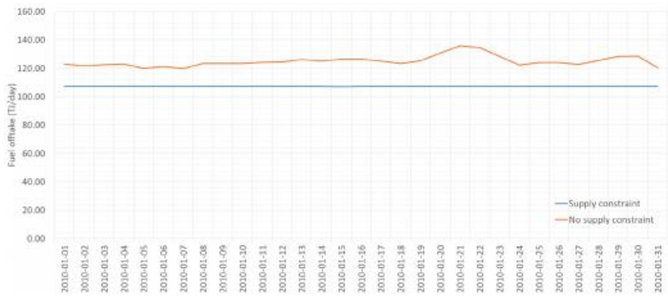

Fig. 6. Fuel offtake (GTP + industrial demand) with and without gas supply capacity constraint at Songo-Songo

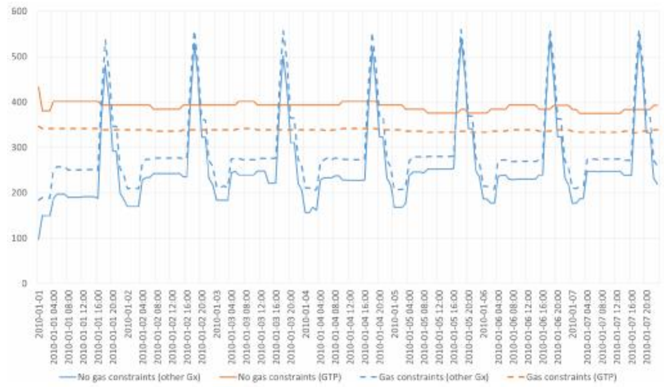

Fig. 7. Representative week of Tanzania generator dispatch (with and without gas supply capacity constraints)

V. CONCLUSIONS

An energy model for EAPP is in development and currently includes hourly level demand and energy forecasts (2010-2038), existing grid connected generators, fuels, emissions and existing/planned inter-country interconnectors with their technical characteristics modelled accordingly. The developed energy model has been used for three case studies demonstrating the benefits of interconnection between EAPP nations, performance of optimal maintenance scheduling and an example of integrated gas-electric modelling in Tanzania.

The use of an energy model of this nature empowers decision makers in utilities, regulatory bodies, government agencies as well as private industry to make informed, risk adjusted decisions on critical infrastructure requirements.

VI. FUTURE WORK

Future work will focus on the further development of the EAPP energy model to gain insights into the EAPP with particular focus on:

- Gas systems in each country including topology of gas fields, pipelines, nodes, demands and storages inclusive of important properties e.g. storage sizes and storage policies, field reserves, max production capabilities, pipeline flow limits and gas demand profiles etc
- Hydro systems in each country including topology of storages, waterways, spillways, linkages to generators inclusive of important properties e.g. storage volumes, natural inflows, max waterway/spillway flows, release policies, value of hydro etc
- Validation of the energy model. The energy model as it stands has not been verified and only representative case studies based on limited data has been presented. The model is envisaged to be validated against historical data whether via interconnector flows, generator dispatch and/or gas flows.
- The development of a long term energy planning model inclusive of appropriate generation, transmission and gas expansion candidates inclusive of appropriate properties e.g. build costs, retirement costs, technical life, min/max units built, WACC etc.

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Table 2 EAPP ELECTRICAL SUPPLY STATISTICS SUMMARY (2010)

Country	Installed capacity (MW)				Share of generation
	Hydro	*Thermal*	*Renewables (excl. hydro)*	*Total*	*%*
Burundi	43	6	-	49	0.1%
Djibouti	-	123	-	123	0.3%
DRC (Eastern)	206	53	-	259	0.6%
Egypt	2 862	20 936	405	24 203	59.9%
Ethiopia	1 850	157	171	2 178	5.4%
Kenya	812	1 099	20	1 931	4.8%
Libya	-	5 255	-	5 255	13.0%
Rwanda	63	42	-	104	0.3%
Sudan	1 778	2 293	-	4 071	10.1%
Tanzania	561	884	-	1 445	3.6%
Uganda	680	127	-	807	2.0%
TOTAL	**8 855**	**30 974**	**596**	**40 425**	**100.0%**
TOTAL (Excl. Egypt)	**5 993**	**10 038**	**191**	**16 222**	**40.1%**

Table 3 EAPP ELECTRICAL DEMAND STATISTICS SUMMARY (2010-2038)

Country	Demand (2010)			Demand (2038)			Average annual growth rate expected	
	Maximum Demand (MW)	*Energy (GWh)*	*Share of energy (%)*	*Maximum Demand (MW)*	*Energy (GWh)*	*Share of energy (%)*	*Maximum Demand (MW)*	*Energy (GWh)*
Burundi	74	421	0.2%	232	1 308	0.1%	2.7%	2.7%
Djibouti	43	134	0.1%	667	1 781	0.2%	10.0%	9.4%
DRC (Eastern)	62	262	0.1%	276	1 187	0.1%	4.5%	4.6%
Egypt	23 729	145 756	69.7%	102 282	666 846	57.7%	4.4%	4.7%
Ethiopia	1 398	5 620	2.7%	15 783	63 455	5.5%	8.7%	8.7%
Kenya	1 445	8 954	4.3%	13 852	86 154	7.5%	8.0%	8.0%
Libya	5 600	32 000	15.3%	29 857	175 239	15.2%	5.4%	5.5%
Rwanda	63	330	0.2%	806	3 890	0.3%	9.2%	8.9%
Sudan	1 357	7 211	3.5%	19 827	105 383	9.1%	9.8%	9.8%
Tanzania	895	5 293	2.5%	6 344	36 873	3.2%	6.7%	6.6%
Uganda	596	3 026	1.4%	2 650	13 025	1.1%	4.5%	4.4%
TOTAL	**35 262**	**209 007**	**100.0%**	**192 576**	**1 155 141**	**100.0%**	**5.5%**	**5.5%**
TOTAL (Excl. Egypt)	**11 533**	**63 251**	**30.3%**	**90 294**	**488 295**	**42.3%**	**7.1%**	**7.0%**

Table 4 ENERGY BALANCE RESULTS (FOR TRANSMISSION SCENARIOS ASSESSED)

		No interconnections	Existing interconnections	Planned interconnections
Load	GWh	209 005.8	209 005.8	209 005.8
Generation	GWh	208 179.7	208 649.7	209 197.8
Losses	GWh	0.0	90.1	300.2
Energy imbalance	GWh	826.0	446.2	108.1
Relative average wholesale cost	#	100%	82%	51%

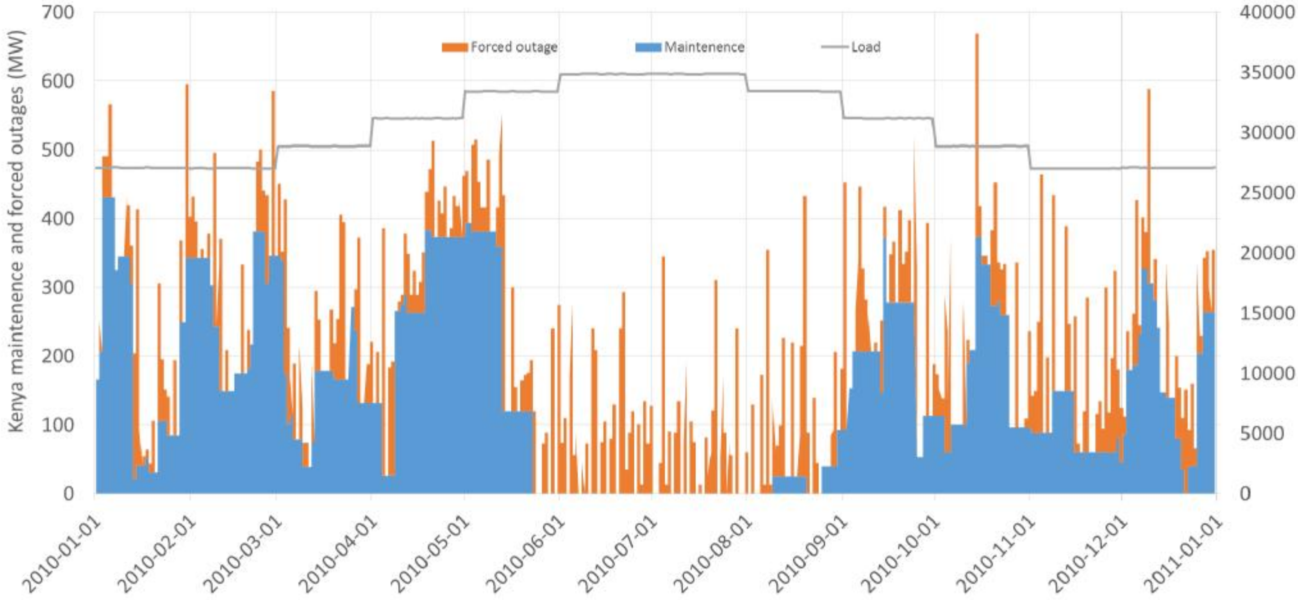

Fig. 8. Kenya maintenance and forced outages with EAPP daily peak demand