A System Dynamics Model of the Nigerian Electricity System

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Abstract—**Policy guides decision. This paper examines policy in the Nigerian Electric Power Sector (NEPS) to cut transmission losses (TL) and improve capacity factor (CF) to 5% and 90%, respectively. A System Dynamics (SD) model developed in STELLA software package was employed to analyze this policy. Secondary data were sourced from: a) National Control Centre (NCC); b) Nigeria Electricity Regulatory Commission (NERC); and c) National Bureau of Statistics (NBS). Two scenarios were considered, the pre-privatized and improved scenarios. Results showed that at TL of 5% and CF of 90% i) electricity outages would be reduced by about 17.84% from 2010 to 2050; ii) over the study period a capacity of 473 MW (about 94.6 MW/year) would be fed back into the system; iii) transmission losses of 3,400 GWh would have been curtailed by 2050; and iv) cutting down TL and improving CF alone in NEPS will not totally curtail electricity outages and deficiencies in NEPS. Therefore, the study recommends that increasing generating capacity (MW) would go a long way in curbing electricity deficiencies. Renewable energy sources could be a better choice. Further studies are recommended in this regard. It was proven by the study that a system dynamics modelling approach is suitable for examining long-term behavior and dynamic feedback in Nigeria's electricity sector.**

Keywords*—*capacity factor, Nigeria, STELLA, system dynamics, transmission losses

I. INTRODUCTION

Electricity is one of the most important value-added commodities to modern human society. Its importance is heightened by its becoming an integral part of social and economic achievements. In recent years, electricity has come as a panacea to the use of petroleum products in transportation sector. Electric vehicles are now technically feasible and economically viable, and various governments have announced the deadlines to eliminate the use of petroleum based vehicles [1]. This development serves to accentuate the need for electricity planning to increase accessibility as priority [2]. The latter statement is accompanied by several challenges, such as: 1) complexities in generation and wheeling capacity; 2) long period and delay in construction; 3) difficulty in storing a large amount electricity; 4) irreversibility of project investment, thus posing severe setback to development, planning in the electricity sector is crucial for development. The aforementioned challenges including high transmission losses (TL) and low capacity factor (CF) were noted for cases of inefficient and unreliable electricity supply in Nigeria [3]-[4]. These factors, coupled with aging infrastructure creates high level of uncertainties. This deprives the plants from attaining their maximum efficiency, therefore making planning difficult [5]. It is however expedient to understand the dynamics involved for policy and proper planning. Application of system dynamics (SD) has been extensively used both as method and tool to aid in resource planning in the electric power industry [6], [7], and [8].

With this backdrop, this study developed a SD model and simulation that can be used to examine the long-term behavior of electricity supply-demand using a STELLA software. The developed model was used to investigate the impact of transmission losses and capacity factor. This was applied to the Nigerian Electricity Power Sector (NEPS). Capability of SD to clearly assess the dynamic behavior of systems has made it an extensively used method and tool in resource planning in the electric power industry and other sectors [8].

II. THE SYSTEM DYNAMICS MODEL

The field of SD introduced by Jay Forrester in the 1960s [9] emerged from engineering feedback control systems and electronics [11]. SD has been relevant in the field of modelling for the past 60 years. SD is a well-established method for modelling and simulation. Its vast capability for visualizing and analyzing complex systems, including dynamic feedback

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systems with interactions between several influencing factors and elements within a system, creates a cause and effect relationship over time [10]. Thus, this justifies the reason for adopting SD to model the NEPS.

Sterman [11] advocated that SD as a method and tool is capable of explicitly taking into account the dynamic behaviors that result from a system due to delays and feedbacks. Therefore, SD can be referred to as a method and set of conceptual tools that enables researchers to understand the structure and dynamics of complex systems. Figure 1 illustrates building blocks of SD, which include: a stock, in and out flows, a converter, and a connector.

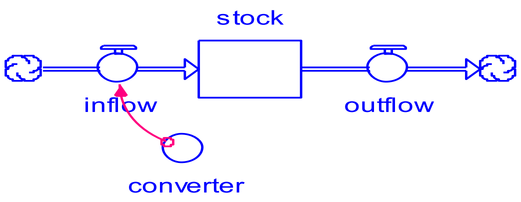

Figure 1. SD building blocks

III. NEPS MODEL DEVELOPMENT AND DESCRIPTION

The developed model in SD made use of dynamic features resulting from feedback in a system [6]. For the purpose of this study, the boundary of the model is limited to the basic operations of the Nigerian electricity system, which include generation, transmission, and distribution as shown in Figure 2. The study assesses the influence and behavior of various dynamic variables of the NEPS over the long-term. It also seeks to reveal the NEPS supply and demand trends over 41 years starting from 2010. Thus, the study, not only captures, but also quantifies the performance in the generation, supply and demand sectors respectively. The influence of TL and CF in the system were assessed using base values of 8.5% and 63%, in that order [5].

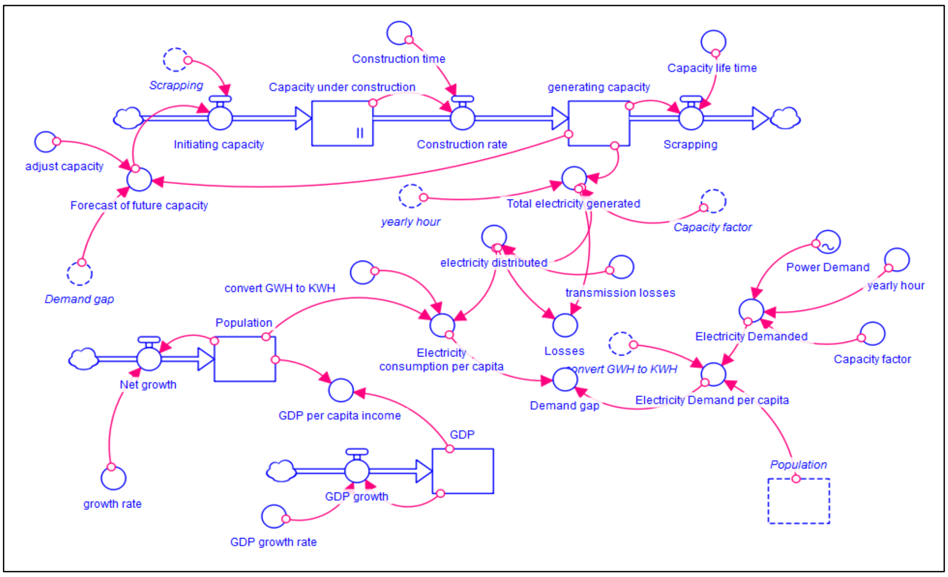

Figure 2. Nigeria Electricity Power Sector, SD Model

A. Data collection

Data were sourced from the Nigerian Electricity Regulatory Commission (NERC), the Transmission Company of Nigeria (TCN), and the National Control Centre (NCC) Oshogbo. Data collected from these sources include the: a) daily peak electricity generation; b) daily minimum electricity generation; c) daily energy recorded; d) national peak demand forecast for the period of 2005 to 2015; e) installed capacity by 2010; and f) available capacity by 2010. Some of the data were then subjected to further analysis to enable estimation of some other variables used in the model, such as capacity factor. Demographic and economic (Gross Domestic Product GDP) data were obtained from the National Bureau of Statistics (2015). Other sources from which data were extracted include International Energy Agency (IEA), World Bank, and published articles.

B. Scenario Development and Parameters

Two scenarios were considered in the study. These are the pre-privatized or base scenario and the improved scenario. The scenarios were determined based on TL and CF values before privatization and NERC planned improvement in the NESP through Multi Year Tariff Order (MYTO) 2.0 [5] as shown in Table 1.

Table 1. Data for parameters used in the scenarios

	Pre-privatized scenario	Improved scenario
TL	8.5%	5%
CF	63%	90%

IV. RESULTS AND ANALYSIS

The model was simulated for period of 41 years spanning 2010 and 2050. This is to capture data of performance for the development and transition of the sector as it became unbundled before being privatized. The Power Sector Reform Act became law in 2005, but the unbundling of the sector went on till about 2013. For this reason, 2010 was chosen as the base year for the study. In addition, electricity generation data obtained from the period of 2006 to 2015 were used for model validation. The leverage points in the model were determined after the model was validated. Leverage points are regarded as points where small changes in parameters can result in large effect in the system (influential parameters that greatly affect the systems behavior) [11]. These leverage points were then used to conduct sensitivity analysis for the electricity system.

A. Pre-privatized/base scenario

The base year for the study is 2010. Data of the NEPS performance for 2010 therefore were used as baseline data to conduct the simulation for the pre-privatized scenario. Pre-privatized or base scenario represents the "*Business-As-Usual, (BAU)*" in NEPS. The driving parameters for BAU scenario were based on TL (8.5%) and CF (63%) as illustrated in Table 2 & Figure 3.

Table 2. Unmet per capita demand. Sources: this study and NERC

Year	Per capita demand (kWh)	Per capita consumption (kWh)	Unmet per capita demand (kWh)
2010	445	121	324
2020	895	327	568
2030	998	419	579
2040	994	482	512
2050	867	498	369

Figure 3 presents the model result of base scenario. It shows the gap between actual electricity generated, electricity consumed, and electricity losses at TL of 8.5% and CF (63%). Also, it shows that total electricity generated (TEG) rose from 20,400 GWh in 2010 to 208,000 GWh in 2050. While electricity distributed rose from 18,700 GWh in 2010 to 190,000 in 2050. The losses also rose from 1,740 to 17,700 GWh in that same year.

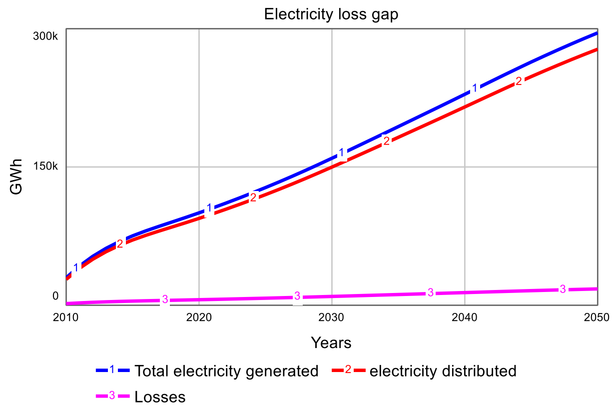

Figure 3. Electricity generated and electricity distributed gap at base scenario

Total electricity generated (TEG), total electricity distributed (TED) and losses at improved scenario are represented in figure 4 has shown an improvement over figure 3. The improvement in 2010 as TEG rose from 20,400 GWh to 29,200 GWh and rose from 208,000 GWh to 286,000 GWh in 2050. Also, TED rose from 18,700 GWh to 27,700 GWh in 2010 and increased by 30.14% in 2050. Similarly, losses were reduced in the improved scenario by 16% compared to the base scenario in 2010 and 19.2% reduction in TL by 2050. This reduction is attributed to transmission losses brought down to 90% in the improved scenario.

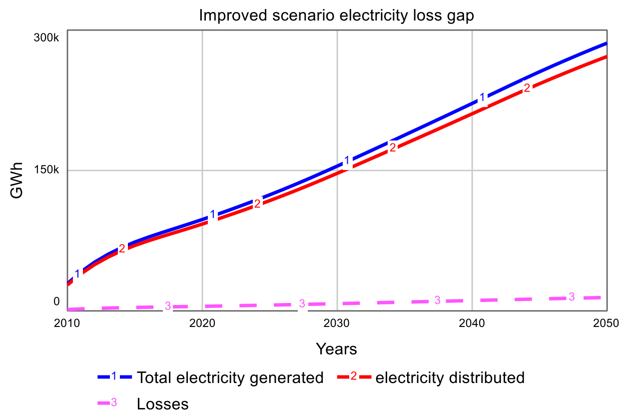

Figure 4. Electricity generated and distributed gap at improved scenario

Figure 5 shows the comparison between the pre-privatized and improved scenarios. The same figure shows an improvement in the TL and CF at 5% and 90% respectively shows a difference of 30.5% in electricity distributed. It is shown that about 9,000 GWh, 29,300 GWh, 45,000 GWh, 64,000 GWh, and 82,000 GWh would be feedback into the system from 2010 to 2050 respectively. This difference represents capacity feedback or losses reduced within the system from improvements on the parameters driving the scenario simulations.

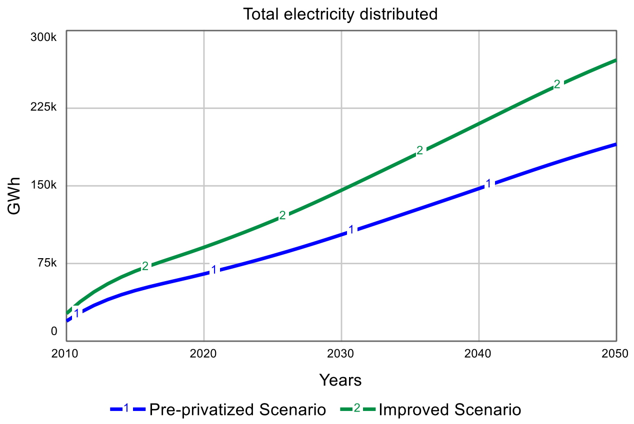

Figure 5. A comparison of pre-privatized and improved scenarios in electricity distributed

In 2010, the value of TEG was 19,540 GWh according to Power Holding Company of Nigeria (PHCN), which is close to the value got from simulation using the model (20,400 GWh). This is evidence of model validation.

V. SENSITIVITY ANALYSIS

The sensitivity analysis (SA) was conducted around the data used for the parameters considered in both scenarios examined in this study. In the SA, the parameter data for Base Scenario were kept constant at TL (0.085) and CF (0.63), while varying that of the Improved Scenario as shown in Table 3.

Table 3. Parameter data used for sensitivity analysis. Source: this study

Run	Capacity Factor	Transmission losses
Run 1	0.87	0.04
Run 2	0.87	0.06
Run 3	0.92	0.04
Run 4	0.92	0.06

A. Total Electricity Generated and Distributed

Figure 6 shows the differences in the results of the SA for the Improved Scenario of the Total Electricity Generated (TEG) for the period under study. Runs represented by sensitivity analysis of total electricity generated (SATEG) from run 1 to 4 as illustrated in Figure 6. SATEG 4, representing CF and TL at 92% and 6% respectively, indicates the highest TEG at 295,000 GWh in 2050, while SATEG 1 at 87% and 4%, respectively had the lowest TEG at 274,000 GWh in the same year. This result clearly shows the role the two parameters - TL and CF - play in the TEG of NEPS.

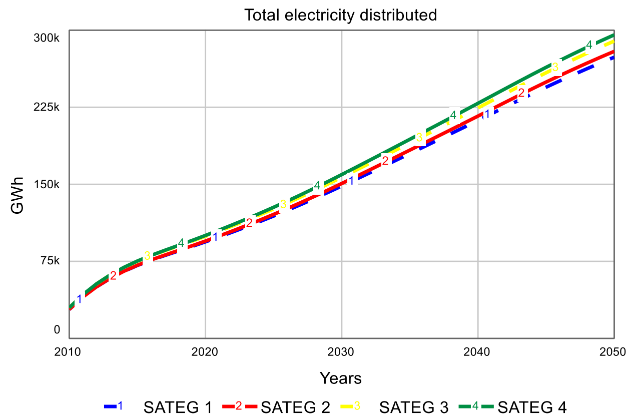

Figure 6. Scenario comparison of total electricity generated.

Figure 7 shows the Total Electricity Distributed (TED). Runs represented by sensitivity analysis for total electricity distributed (SATED) from run 1 to 4 is shown in Figure 7. SATED3 and 4 at (92%, 4%) and (92%, 6%), respectively have the highest electricity distribution of 278,000 GWh in 2050. This is attributed to the CF where 92% was the highest.

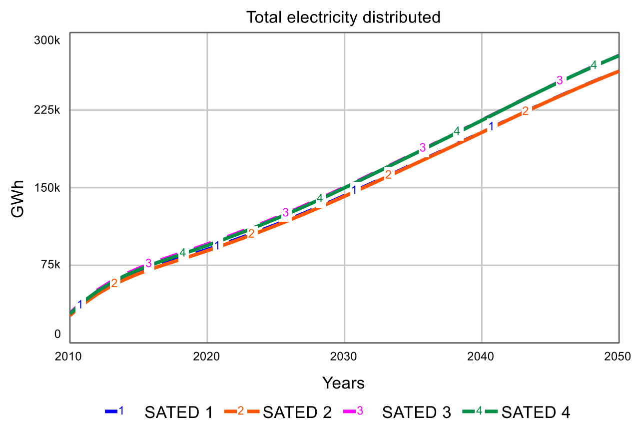

Figure 7. Scenario comparison of total electricity distribution.

The trend in TED was also observed for consumption as shown in Figure 8. This therefore supports that the system can be optimized at 92% for CF and 4% for TL.

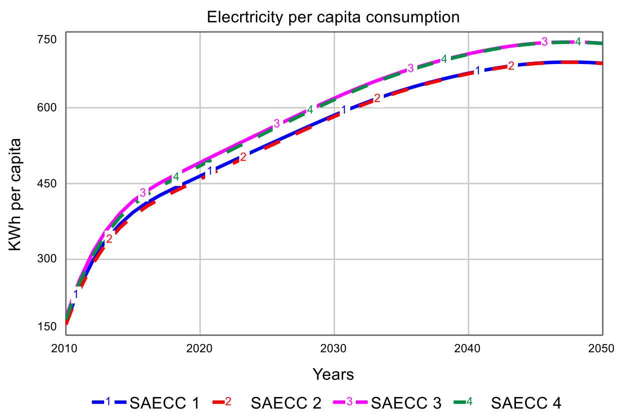

Figure 8. Scenario comparison of electricity per capita consumption

Figure 9 shows the result of the sensitivity analysis for the ratio of electricity demand unmet to consumption. Represented by sensitivity analysis for electricity demand unmet ratio (SAED) from run 1 to 4. It indicates that run 1 and run 3 indicated more electricity demand met in the period from 2010 to 2030 by about 1.45% compared to SAED 2 and 4. After 2031, all runs showed a common trend. This implies that a reduction in TL alone will not curtail the challenges of electricity demand unmet ratio in NEPS in the far future (2031 - 2050).

It is noteworthy that Figure 9 affirms the optimization scenario run observed in figures 7 and 8.

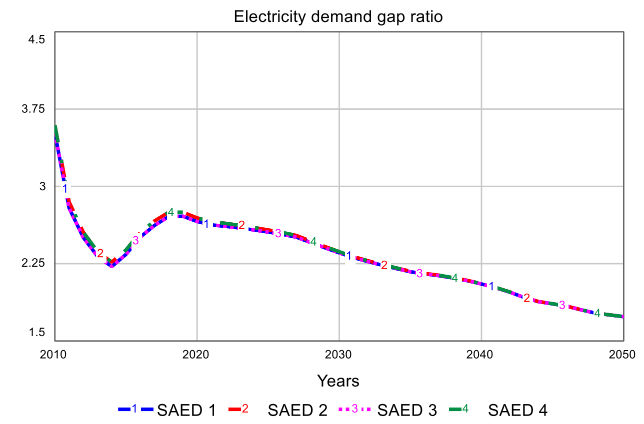

Figure 9. Sensitivity analysis for electricity demand gap ratio

Figure 10 indicated that with SAFC 3 capacity needed for future would be reduced compared to other runs. Therefore, Figure 10 serves to show that sensitivity analysis run 3 (0.92, 0.04) is the optimized system parameters as observed in Figures 7, 8, and 9.

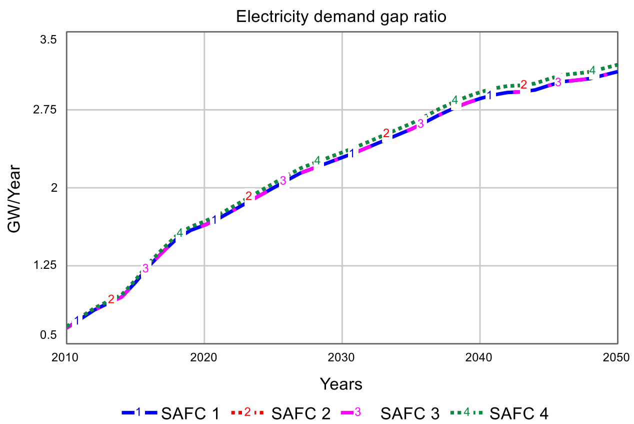

Figure 10. Sensitivity analysis of future capacity needed

VI. CONCLUSION

A System Dynamics (SD) model developed in STELLA software package was utilized to analyze the Nigerian Electricity Power Sector (NEPS). Looking at the future trends of the NEPS from the results stand point of the simulation model, it was observed that transmission losses and capacity factor were two key parameters that played a critical role to improve the sector. This was further established from the sensitivity analysis conducted in the model. Therefore, improving on the parameters, such as the capacity factor (CF) and transmission losses (TL) amongst others as desired in the MYTO 2.0 of the NERC, will lead to low hanging means of improving on the system performance.

REFERENCES

[1] A. Petroff, “These countries want to ditch gas and diesel cars,” 2017. [Online]. Available: http://money.cnn.com/2017/07/26/autos/countries-that-are-banning-gas-cars-for-electric/index.html. [Accessed: 18-Oct-2017].

[2] C. G. Norela constantinescu, Christos dikaiakos, “Research, Development and Inovation road map 2017-2026,” *ENTSO-E aisbl*, 2016. [Online]. Available: http://riroadmap.entsoe.eu/wp-content/uploads/2016/06/entsoe_ri_roadmap_2017-2026.pdf. [Accessed: 15-Oct-2017].

[3] F. Oladipo and O. Temitope, “The Nigerian Power System Till Date”: A Review , vol 1, issue 5, October 2014. .

[4] M. S. Adaramola, S. S. Paul, and S. O. Oyedepo, “Author ’ s personal copy Assessment of electricity generation and energy cost of wind energy conversion systems in north-central Nigeria,” 2011.

[5] NERC, “Multi-year tariff order for the determination of the cost of electricity generation for the period 1 june 2012 to 31 may nigerian electricity regulatory commission 1 st june 2012,” 2017, no. June 2012, pp. 1–37.

[6] A. S. Momodu, A. Addo, J. K. Akinbami, and Y. Mulugetta, “Low-carbon development strategy for the West African electricity system : preliminary assessment using System dynamics approach,” *Energy. Sustain. Soc.*, vol. 7, no. 11, pp. 1–23, 2017.

[7] Y. Moumouni, S. Ahmad, and R. J. Baker, “A system dynamics model for energy planning in Niger,” *Int. J. Energy Power Eng.*, vol. 3, no. 6, pp. 308–322, 2014.

[8] A. Ford, J. Wright, and F. Prize, “System Dynamics and the Electric Power Industry,” vol. 13, no. 1, pp. 57–85, 1997.

[9] Y. Y. Feng, S. Q. Chen, and L. X. Zhang, “System dynamics modeling for urban energy consumption and CO 2 emissions : A case study of Beijing , China,” *Ecol. Modell.*, vol. 252, pp. 44–52, 2013.

[10] Á. Robalino-López, Andrés and García-Ramos, José-Enrique and Golpe, Antonio A. and Mena-Nieto, “System dynamics modelling and the Environmental Kuznets Curve in Ecuador (1980-2025).,” *Energy Policy*, vol. 67, pp. 923–931, 2014.

[11] Sterman John.D, *Business Dynamics: System Thinking and Modeling for a Complex World*. McGraw-Hill, 2000.