Digital Twin Framework for Holistic and Prognostic Analysis of the Nigerian Electricity Supply Industry: A Proposal

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***Abstract*—The provision of stable electricity supply remains the backbone of economic, social, and political developments of any nation, especially in the current digital-driven economy. In recent years, the Nigerian Electricity Supply Industry (NESI) has been struggling to achieve a productivity factor of 0.29, which is far below the international standard of 0.80. This abysmal achievement is far contrary to the huge financial commitments and socio-technical driven policies that have been formulated by successive governments to address continuous electricity grid collapse for over four decades. In order to address this endemic and epileptic electric supply, previous research efforts were directed to studying the individual components of NESI or policy formulations amongst others. To the best of our knowledge, research to holistically investigate all the components, their interactions and the effects of formulated policies on NESI operational efficiency is yet to be undertaken. Thus, this paper finds NESI to be a component of a System of Systems (SoS). Hence, it presents a novel framework that is premised on a SoS and digital twins. Also, the framework employs system engineering best practices to holistically analyse the problems bedevilling NESI operations with the primary aim of increasing productivity factor while reducing the rate of grid collapses. In reality, the supply of uninterrupted electricity to all sectors and citizenry is not negotiable for Nigeria to achieve the desired economic transformations and diversifications.**

Keywords — NESI; Nigerian Electricity Crisis; Systems Thinking; System of Systems; Digital Twin

I. INTRODUCTION

It is indubitable that a stable and reliable supply of electric power is paramount to the survival of every other sector of a country in the current era. A recent study [1] suggests that a nation requires a strong and reliable power infrastructure to achieve a strong economy, standard educational system, improved healthcare, regional and national growth, as well as social and economic inclusions for the citizens. Similarly, it is reported [2] that a healthy and robust power sector is a must for Nigeria to achieve her much desired economic diversification and transformation.

ISBN 978-1-7281-8081-6/21/$31.00 ©2021 IEEE

Unfortunately, this vital infrastructure has defied all apparently aggressive reforms and huge capital expenditures by, successive regimes on the power sector. As at 2012, Nigerians had one of the poorest power supplies in the world with a per capita consumption of 0.03KW (Kilowatts), thereby, ranking far below other developing nations like Cuba, Egypt, Libya, Iraq and South Africa with per capita consumptions of 0.38KW, 0.265KW, 1.015KW, 0.42KW, and 1.015KW respectively [3]; almost a decade after, there are no pointers to such improvement in the decades to come. A recent study [2], reports that about 40% of Nigerians lack access to electricity while those that have access mostly receive epileptic supply. Similarly, the NESI had targets of 11,879MW (Megawatts), 14,218MW and 40,000MW by 2012, 2013, and 2020 respectively but the installed capacity as at 2019 still stood at 7,000MW [2]. The Transmission Company of Nigeria (TCN) celebrated a meagre all-time peak transmission of 5,420.30MW in mid-August 2020 [4] while investigations report that the nation has consistently experienced tens of grid collapse incidences per year since late 1980 [5-7]. According to [8], while Nigeria currently requires about 240,000 MWh (Megawatt-hour) of electricity to achieve uninterrupted supply to consumers, NESI can barely generate about 81,122 MWh. A recent assessment of NESI from 1996 to 2015 estimated the productivity factor of NESI to stand at 0.29 as against the international standard of 0.80 [9].

Ironically, this abysmal performance of NESI is despite remarkable financial commitments of the government to the power sector. Over US$ 30 billion was expended by successive regimes on NESI between 2005 and 2014 without any significant benefit to the consumers [10]. In addition to paying electricity subsidies amounting to ₦ 1.12 trillion between 2015 and 2018, the government gave a loan of ₦ 213 billion to distribution companies in 2014 to stabilise electricity market, approved ₦ 701 billion in 2017 as Power Assurance Guarantee for a period of two years, and released ₦600 billion to the power sector in 2019 to cater for the shortfalls in the sector [2]. The Ministry of Power also enjoys the third-highest allocation on capital expenditure in the 2020 national budget [11].

In addition to monetary expenditure, successive regimes have initiated reforms in the NESI. The peak of such is the enactment of the Electric Power Sector Reform Act (EPSRA) of 2005 [12] as the legal framework for the transfer of assets and liabilities of the defunct National Electric Power Authority (NEPA) to an initial Power Holding Company of Nigeria (PHCN). The Act also established the Nigerian Electricity Regulatory Commission (NERC) as a government regulatory agency to ensure compliance with the provisions of the Act at all levels. To get private investors into the industry, the Government unbundled the PHCN in 2013, into three separate markets for electricity generation, transmission and distribution operated by the Generation Companies (GenCos), Transmission Company of Nigeria (TCN) and Distribution Companies (DisCos) respectively.

Within the last decade, several studies that appraised the performances of the EPSRA vis-à-vis its set targets from social-economic, social-political and technical perspectives have concluded that the privatization of the power sector has not transformed into a significant improvement in electricity supply as expected by the government as well as the consumers at all levels [10, 13].

It is evident from the foregoing that projects, reforms and policies proposed for NESI need to be subjected to rigorous verifications before implementation to ensure they will yield desired results in the face of the influences of the various forces in the infrastructural eco-system. Arguably, such verifications will offer evidence-based guides to the decision and policy makers on whether or not their intended steps are in the right direction. The pertinent scientific questions to be answered by the computing research community in this case therefore are:

i. Why do government policies and reforms on NESI often fail to yield the anticipated results?

ii. How can the impact (positive or otherwise) of a proposed reform or policy on NESI be tested before its implementation?

iii. What IT-based solution(s) can be deployed to meet the challenges posed in (*i*) and (*ii*) above?

Intuitively, these multifaceted questions cannot be exhaustively answered in one article. Thus, the present paper does not only propose a research roadmap towards answering these questions but is to also stimulate the computing research community to expend efforts in this direction to seek workable solutions to the intractable electricity crisis in Nigeria.

In reality, NESI is a component of a System of Systems (SoS) in which each component is in a number of feedback loops resulting from live influences of other members of the ecosystem. Hence, a comprehensive study and analysis of NESI must take these mutual and dynamic influences into consideration to simulate the runtime readjustments in each subsystem that can help the overall SoS meet its set targets. As a first step towards answering the above questions, this paper proposes a conceptual digital twin framework for computational study of NESI as a system in a SoS under the various influences of the other components of the SoS to be able to forecast the productivity factors that will follow the implementations of policies and reforms. The computational analysis of such SoS will be used to study and/or predict the key performance indices of the NESI under specified environmental conditions. The significance of the computational framework is that its implementation will be a software system that provides scientific and evidence-based guides to the policy and decision makers in their efforts to evolve appropriate institutional framework for the management of the energy supply value chain.

The next section presents a discussion of related works in the literature. This is followed by an overview of the current components of NESI in Section 3. Section 4 presents the proposed conceptual framework while the paper concludes in Section 5.

II. RELATED WORKS

Several research efforts have been made, from different perspectives, in search of workable solutions to the hydra-headed problems of NESI across all stages in the energy cycle from generation through transmission and distribution to consumption.

The work in [14] combined the Multi-Attribute Utility Theory (MAUT) method with entropy technique to propose a Multi-Criteria Decision Making (MCDM) framework for selecting among the competing solutions, proffered in the literature, to electricity generation problems in NESI. Having identified twenty-three factors hindering adequate power generation from an extensive survey, they ranked the priorities of the factors based on the number of articles citing them in the literature. Their technique selected a reliability centred maintenance approach as the solution to the problem of poor maintenance of generation infrastructure and a diplomatic approach to the problem of militancy and vandalism. While this approach appears interesting, we opine that the frequency of citation of a problem published works is not a sufficient criterion to effectively rank its severity relative to other problems. Arguably, a less popular problem can pose more danger to the system even while it is still waiting to be discovered. Moreover, the scope of the work presented in [14] is limited to the generation sub-unit of NESI, such initiatives need to be extended to cover other stages of the energy cycle for a holistic analysis of the global problem.

In another research [15], Analytical Hierarchy Process (AHP) was used to investigate the holdup to power generation in NESI. The researchers used AHP to analyse the responses to interview questions from respondents in nine electricity generation companies. Their findings reported poor reliance on obsolete equipments with poor maintenance culture, shortage of expertise coupled with non-transparent recruitment processes, poor staff welfare and community disturbances as some major factors inhibiting the capacity of NESI to generate enough power to meet the increasing demands from Nigerians. They suggested a restructuring and diversification of the economy and a mix of generation from different sources to solve the problems of power generation. In similitude to [14], the scope of [15] is limited to the generation stage of the energy cycle while problems exist at all stages of NESI.

The authors of [16] used the Harvey logistic model to forecast the demand and supply of electricity in Nigeria over a period of 21 years. The model used was built based on the historic data obtained from the use of General Autoregressive Conditional Heteroscedasicity (GARCH) model to estimate the market volatility in NESI between 1970 and 2005. Their findings acknowledged the obvious fact that the national demand for electricity greatly exceeds its supply and their study concludes that NESI is a fertile land for investment. However, the model used did not take into consideration the reasons for the failures of previous investments in the industry in order to avoid (or at least mitigate) such failures of subsequent investments.

A study [17] suggests a few steps to end the energy crisis in the country. The suggested steps include increased provision of technical components, personnel (re)training, as well as the review of the energy policy to accommodate and encourage private investments in the power sector. Interestingly, the energy policy has been reviewed and implemented to accommodate private investors for about a decade and the impact has been more darkness to the consumers than ever before. Hence, we argue that, it is not sufficient for a revised policy to address funding problem (through private investment) in isolation; rather a holistic view of the system will be required to verify that the new policy will yield the much desired results when implemented.

Another study [18] reported poor policy initiatives and regulation, vandalism and theft of power infrastructure, inadequate gas supply, use of obsolete equipment and poor maintenance culture as the major causes of erratic power supply in Nigeria. They suggested the enactment of sound policy framework to ensure an efficient utilisation of available energy by consumers. A similar but independent investigation [19] also reported inconsistent and misguided government policies, lack of expertise, and inefficiency in the entire energy cycle from generation through transmission and distribution to consumption. In fact, the researchers postulate that the problem of NESI is neither low generation nor inadequate distribution but inefficient consumption. They suggested, as possible solutions, the development of policies on conservation of energy and upgrading of equipment across the energy cycle.

A research [20] reports an analysis of the public policies affecting the NESI from 1999 to 2019 using the neo-liberal theory. The researchers argue that the reforms in NESI have not yielded the expected results because the privatisation policies are more favourable to foreign institutions and bilateral participants than the indigenous participants; thereby leading to grudges at some quarters. They claimed that a Nigerian model of the neo-liberal policy must be developed, which should involve a critical mass of the Nigerian elites and professionals in the formulation and implementation of reform policies for NESI. They argued further that without such a systematically developed Nigerian model of the neo-liberal policy, which should also take the prevailing economic condition of Nigeria into consideration, the nation will continue to invest time and resources in NESI without getting the expected results.

In general, existing research works on the problem of NESI are targeted at analysing some different aspects of the industry; ranging from power generation [14, 15], through market volatility [16] to policy formulation [17-20]. Furthermore, the proponents of review and formulation of energy policies in the literature have not considered how to subject such new or reviewed policies to tests before their implementations. Since several policies have failed in the past to yield their much expected results, it has become paramount to bridge this information gap through some rigorous verification of the impacts of such policies on the performance indices of various elements of the ecosystem of NESI. Hence, in order to unravel the mystery of the seemingly irreversible failure of NESI, this paper considers the deployment of a digital twin of core components of NESI to systematically and holistically do diagnostic and/or prognostic analysis of the system in real-time as well as forecast the performance of a policy/reform even before its implementation.

III. AN OVERVIEW OF NESI

Fig. 1. presents an overview of the key participants in NESI based on the information available on the website of Nigeria Electricity Regulatory Commission (NERC) [21]. Each participant in the figure has some well-defined Key Performance Indices (KPIs). At present, there are more than 10 GenCos contributing to the grid and 11 DisCos supplying an estimated population of over 180 million.

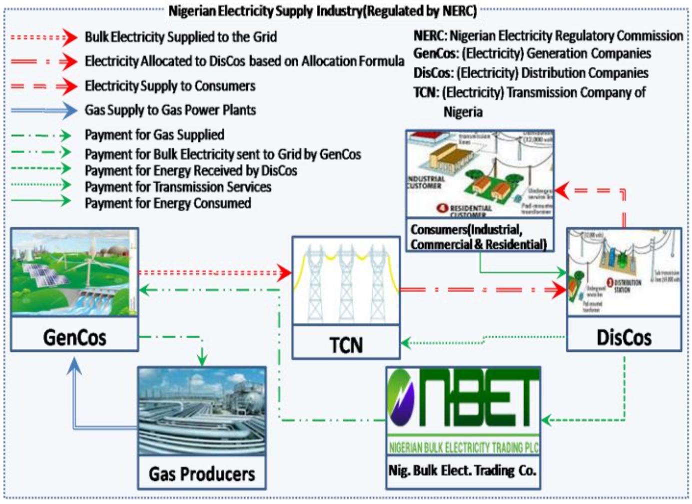

Fig. 1. Overview of Nigerian Electricity Supply Industry

The GenCos supply their generated energy as bulk electricity to the national grid which is being operated by the TCN to wheel the energy to the 11 DisCos, each of which has exclusive coverage of some specific geographical area. The DisCos draw electricity from the grid based on an allocation formula and sell to the customers within their jurisdictions. DisCos pay the Nigerian Bulk Electricity Trading Company (NBET) for the energy allocated to them from the grid. DisCos also pay the TCN for transmitting the energy from the GenCos to them. NBET is responsible to pay the GenCos for the energy they supply to the grid. Thus, NERC regulates the activities of the various players in NESI and mediates between them at times of disputes.

IV. SYSTEM OF SYSTEMS DIGITAL TWIN FRAMEWORK FOR HOLISTIC AND PROGNOSTIC STUDY OF NESI

This section presents a proposal of a computational framework, using a combination of systems thinking and digital twins (DT) approaches, as a response to the research questions posed in Section 1. The section starts with brief theoretical foundations to the systems thinking and DT methodology and followed by the proposed framework.

A. Overview of Systems Thinking and Digital Twins

Systems thinking is a component of systems engineering that offers a framework for relating systems to their environments in order to understand complex problem situations and manage risks and uncertainties to maximise performances while preventing or mitigating unintended consequences [22]. In essence, systems engineering generally seeks to proffer solutions to complex problems in the face of complicated socio-technical relationships.

Fig. 2 is a description of a typical systems thinking approach in combination with DT. The DT (computational model) at the centre of the diagram is an abstract and subjective representation of the real world/physical twin (PT) specified using appropriate formalism. The computational engine (CE) implements the protocols and algorithms for analysing the DT to generate results. This can be based on analysis techniques such as simulation, machine learning, deep learning, etc. as the case may be. One important attribute of the DT is that it is a dynamic model in that it receives regular updates from its PT which is also a dynamic system to ensure that the former is always a true representation of the latter. The choices of CE and formalism with which to create the DT depend on factors such as the properties of the PT, user's experience, etc. The CE executes the model to generate results which provide feedback to the analyst as more insights into the real world. The analyst uses the feedbacks received as a guide to redesign the DT or adjust system properties before the next iteration of model execution until the desired results are obtained. The results can also serve to predict the states of the PT under some specified conditions in the future.

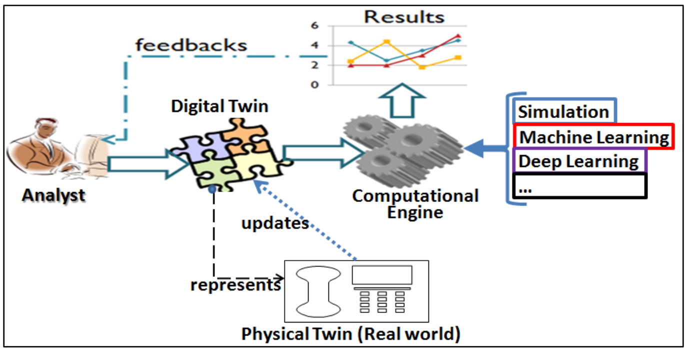

Fig. 2. Schematic illustration of systems thinking approach with Digital Twin

B. NESI as a System of Systems

A public infrastructure, such as NESI, is considered to exist in a complex eco-system, which is a network comprising not only its various components but also its surrounding economic, social, geographical, political systems as well as the socio-political and techno-social orientations of the majority of the organizations and individuals that interact from within and outside the infrastructure [23, 24]. In addition to the power ministry which has the statutory duty to define policies and directions for NESI, other ministries such as water, and petroleum resources as well as solid minerals also have roles to play in the supply of necessary inputs to the electricity generation processes [20]. Systematically, they form a System of Systems (SoS) in which each independent component (system) exerts great, yet un-noticed, influences on the performance and productivity of the infrastructure.

According to the International Council on Systems Engineering (INCOSE), SoS engineering generally requires considerations beyond thoughts usually associated with engineering to include socio- technical and sometimes socio-economic phenomena [25]. Adverse socio-political and socio-economic factors, such as high corruption index, are believed to exert significant influences on the productivities of such infrastructures [26, 27]. However, stakeholders rarely pay attentions to such influences; rather they mostly concentrate on the technical components of the infrastructure itself to look for the impediments to its success. According to [28], a holistic measurement of the productivity of an infrastructure should identify and analyse its performance variables that can serve as guides in the formulations and implementations of policies towards a general improvement of the infrastructure.

C. Conceptual Framework of NESI as an Infrastructural Eco-System

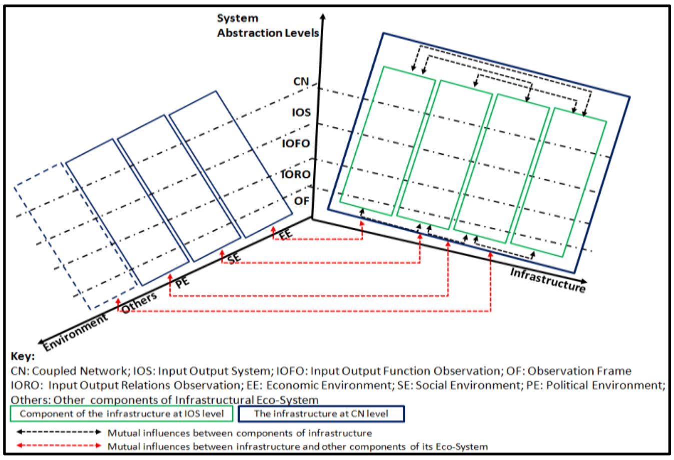

Fig 3. Conceptual framework to investigate the interplays in the Infrastructural Eco-System of NESI

The 3-dimensional system in Fig. 3 is an abstract view of the proposed SoS simulation framework for holistic study of NESI as an infrastructural eco-systems. For a separation of concerns, we consider the modelling of an infrastructure and its surrounding systems in the eco-system in separate planes of the 3-dimensional (3-D) architecture. That is, the infrastructure is modelled in the System Abstraction Levels-Infrastructure plane, while the System Abstraction Levels-Environment plane contains the models of the relevant components of the infrastructure's social, economic, political, climatic environment as well as security in both the physical and cyber domains. In each case, we propose the system-theoretic approach to system specification at different levels of abstraction as defined by [29] and denoted by the System Abstraction Levels axis to derive, and specify, the models of the various components of the eco-system (and their sub-components). Since the eco-system is made up of disparate components with diverse system variables, we will need a multi-formalism modelling approach to effectively represent the different elements. Consequently, a hybrid simulation approach will be adopted for a simulation-based analysis of the internal mutual influences between the components of the infrastructure itself and the external influences between the infrastructure and other members of its eco-system.

The Infrastructure-Environment plane of the 3-D systems contains the specifications of the mutual influences, which model the typical loose integration between the distributed components of the eco-system in reality. It is worthy to note here that this loose integration is different from the tight coupling of the components of an independent system as prescribed in the Coupled Network (CN) abstraction level and represented in the Infrastructure axis by enclosing the physical components of an infrastructure within itself. Rather this loose integration models the peer influences that lead to changes in the values of some model parameters without changing the system's state. A similar approach [30, 31] has been employed to study the interplays between the components of the healthcare system.

D. Implementation Procedure for the Conceptual Framework

In order to adopt and implement the conceptual framework presented in Fig. 3, a 5-step procedure is proposed as shown in Fig 4. Basically, the procedure is meant to holistically investigate the interplays among the various elements of an infrastructural ecosystem such as NESI. This would require choosing suitable formalisms, CE and execution environments.

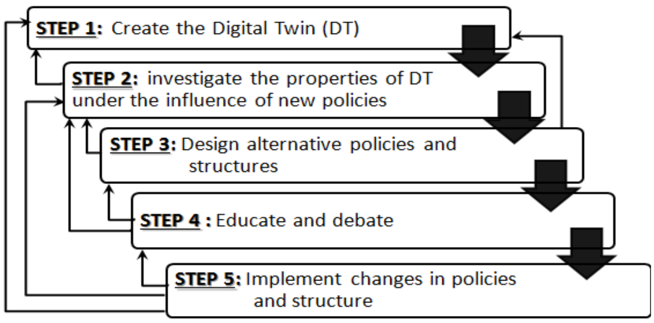

Fig 4. Systems analysis process with the computational framework

An investigation of the infrastructure begins with the formulation and specification of the DT of the PT and its relevant environmental factors in STEP 1. Such models to be explored may include:

- Formal models of the obvious and subtle components of NESI as a SoS.
- Formal definitions of the mutual influence of the different components of the SoS on one another.

The components and the mutual influences to be captured in the modelling process would be such that they help the policy makers to gain a better understanding of the open and hidden behavioural characteristics of the ecosystem. The models may also need some formal validations to be sure they truly represent the intended system.

STEP2 is the execution of the model specified in STEP 1, typically with suitable CE that can accept the required parameters. Unrealistic behaviours of the model may necessitate iterations of the first two steps to refine the models in STEP 1 until a satisfactory degree of confidence is attained about its descriptions of the problems at hand. The trajectory (results/traces) of the computational analysis in this step is expected to provide sufficient information to infer or forecast the impacts of proposed policies and reforms on certain Key Performance Indices (KPIs) of NESI.

Based on the knowledge gained from the results of STEP 2, STEP 3 involves the definition of alternative policies or reforms for verification. An alternative policy, in this case, may be borne out of the refinements/readjustments of the one previously simulated in STEP 2 or a completely different one. Thus, several iterations of steps 1-3 may be required for the analysts to determine which of the tested policies or reforms has the greatest potential to bring about the desired improvement to the system.

Having elicited the obstacles to the system and subsequent determination of alternative processes through iterations of steps 1-3, the next step would intuitively be the implementation of the newly found solutions. Implementing new solutions will, in most (if not all) cases, lead to organisational changes with attendant resistances from some vested interests. STEP 4 covers the process of change management by the leadership of the organisation. This encompasses the strategic process of educating the stakeholders to subdue their resistances to the change. While this change management process is technically not part of this framework, some stakeholders may raise questions or concerns that require further iterations of steps 1-3 for discussions.

STEP 5 covers the implementation of the new policy or reform. Further iterations over the earlier steps may at times be required for training purposes or to address new issues that may arise during implementation.

V. CONCLUSION

The electricity crisis in Nigeria has not only defied all efforts of governments and concerned citizens to remain intractable for decades, but is also threatening to continue indefinitely. Hence, a systems thinking approach is necessary, at this point, to look beyond the conventional boundaries in order to unravel the mystery of the continuous failure of NESI.

This paper has proposed a conceptual framework, using the systems thinking DT approaches, for holistic and predictive investigations of the mutual influences of the various components of the system the environments within which it operates.

The paper seeks to provoke the thoughts of interested researchers to consider the system thinking and DT approaches in their elicitations of the problems of NESI and workable solutions. We are optimistic that research efforts in this direction will produce scientific and evidence-based decision support software tools to the policy makers in NESI to verify and validate policies and reforms in the power sector before their implementations.

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