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A Multi-Perspective Modeling and Holistic Simulation Framework for the Energy Sector

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Abstract: Energy has become a panacea for a rapid development of any modern human society. Non-renewable energy generation systems are put under tremendous pressure to transition toward a more sustainable energy that reduces impact on climate change while enhancing energy efficiency and securing energy supply. Energy systems however, exhibit complex dynamics leading in most cases to reductionist approach studies that mainly examine the components of the system in isolation. This paper proposes a multi-perspective modeling of the ES through a structural adjustment of its components using multiple formalisms as follows: (i) an ontology was built which is, a formal specification of energy simulation knowledge, based on agreed upon concepts and their relationships as found in the literature review of the energy simulation domain, (ii) a simulation framework was proposed around the identified perspectives that are most often discussed in findings of energy simulation. Each perspective is specified in a fitting formalism and represents a family of models with specific objectives that drive simulation studies of the energy sector, and (iii) an integration mechanism was developed to unify the isolated perspectives into an overall holistic model such that parameters are mutually influenced by one another in a live simulation for a comprehensive study of the energy sector. Results showed that power supply failure caused by persistent tripping of transmission line was due to a sudden increase in generation power plants. The failure was successfully re-adjusted through perspectives integration during live simulation to fit with the maximum wheeling capacity of the power transmission grid component. The updated values of the transmission parameters have also matched with the expected outputs of the consumption component parameters at the receiving end. Hence, the study has produced closer and efficient results for long-term performance evaluations of the energy demand fulfilment.

Keywords: Energy Systems, Modeling and Simulation, Multi-Paradigm Modeling, Holistic Simulation, Ontology-Driven Simulation

1. Introduction

Energy is an essential commodity for a stable and reliable modern economy. The energy sector powers multiple other sectors such as education, healthcare, transportation, and industry that strongly rely on an efficient power infrastructure [34]. Energy system is comprised of several components including production, transportation, distribution, consumption, and finances, which communicate with one another through intricate processes in a complex relationship. Lately, the need to transition from non-renewable source of energy to renewable source of energy due to climate change has put the energy systems under tremendous pressure while population growth and fast-paced industrialization also increase energy consumption greatly. This challenge attracted significant research attention on the energy sector using various models including computational, mathematical, and physical models [46]. Energy systems (ES)s however, exhibits complex dynamics due to their various and diverse components leading in most cases to isolated studies that mainly examine the components of the ES separately while failing to consider the interconnections that exist between these components, thus limiting the understanding of the ES as a complete whole for better decisions making. Models that consider economic factors play crucial role in energy decision-making, and they include economic indicators such as investment costs, operational expenses, and financial mechanisms. They can analyze the cost-effectiveness of different energy sources, pricing mechanisms, and the impacts of policy instruments like subsidies or carbon pricing [6, 42, 49]. Economic factors are often integrated into energy system optimization models or cost-benefit analyses. Models that address environmental factors are critical for energy systems and deal with aspects such as such as greenhouse gas emissions, air pollution, land use, and water consumption [3, 32, 47]. They can assess the environmental impacts of different energy technologies and policies, helping to identify low-carbon and environmentally friendly pathways. Life cycle assessment and environmental impact assessment methods are commonly used in such models. Models dealing with social factors highlight the significance of social inclusion and account for social factors by considering aspects such as energy access, energy poverty, employment, health, and social acceptance of different technologies. These models can assess the distributional impacts of energy policies, equity considerations, and social acceptance barriers to energy transitions [23, 24, 36, 48]. Stakeholder engagement and participatory modeling techniques are often used to capture diverse social perspectives. Models addressing technological advancements and innovation shape energy systems and incorporate technological factors such as energy technologies used, costs, efficiencies, and scalability. They explore the role of emerging technologies, like renewable energy sources, energy storage, and smart grids [5, 9, 37, 40]. Technological factors are often integrated into energy system models, energy scenario analyses, and technology diffusion models. Policy frameworks and regulations significantly influence energy systems and they analyze the impacts of policy instruments such as renewable energy targets, carbon pricing, energy efficiency standards, and regulations on energy markets, [15, 28, 29, 60]. These models evaluate the effectiveness and interactions between different policies, identify policy trade-offs, and assess policy pathways for achieving sustainability goals.

We argue that there is a need to develop a unifying simulation framework that incorporates these different aspects of the energy system together to support researchers and policymakers to develop more comprehensive and holistic models that account for the diverse dimensions of the energy sector. We propose a multi-perspective modeling and holistic simulation (MPM&HS) framework that allows simulation parameters to be lively and mutually influenced by one another to produce closer and efficient results for a long-term performance of the energy sector. MPM&HS is a well proven and rigorous approach that was successfully applied to study complex systems such as healthcare systems, and traffic systems [13, 53, 51]. In this work, the MPM&HS framework addresses the followings:

1) Build an ontology based on an extensive literature review that is comprised of all the agreed upon concepts and their relationships in the domain of modeling and simulation of energy systems;
2) Formulate the level of abstractions that correspond to the various perspectives in energy simulation domain. These abstractions represent each a family of models with specific objectives that drive simulation studies of the energy sector.
3) Integrate these different perspectives into an overall holistic simulation model within their respective experimental frames through model output-to-parameters in a live simulation to derive closer results to the reality.

The rest of this document is organized as follows. Section 2 presents related works and highlights the originality of our approach. Section 3 presents the conceptual and operational framework (multi-perspective modeling and holistic simulation). Section 4 shows how the approach was used in a running case study of the Nigerian energy system. Section 5 presents a discussion of the results obtained. Section 6 concludes the article.

2. Related Works

The energy sector plays a crucial role in modern societies, and the efficient management and planning of energy systems are vital for sustainability and economic growth. To achieve this, major developments have been made by researchers these last decades exploring various ways ranging from modeling approaches – computational, mathematical, and physical models - to the fields - process systems engineering, and energy economics [46]. The energy sector is a complex and dynamic field that requires comprehensive modeling and simulation frameworks to understand and optimize its operations. One common way of addressing this complex system is the use of multi-perspective modeling and holistic simulation, which provides a comprehensive understanding of the intricate interactions of the sub-components and dynamics within the energy sector. Multi-perspective modeling is a concept mostly used in various fields to analyze complex systems from different viewpoints or perspectives [13, 16, 17, 51, 55]. Multi-perspective modeling in the context of the energy sector involves integrating multiple viewpoints or perspectives to capture the complex and interconnected nature of energy systems. This approach recognizes that the energy sector is influenced by various factors, including economic, environmental, social, technological, and policy-related aspects [1, 7, 10, 18, 38]. To highlight the need for alternative estimates and modeling approaches to capture the complexities of the energy sector, a study was conducted in [45] on gaseous and primary aerosol emissions in Asia in the year 2000. They used the RAINS-Asia simulation model to generate a comprehensive picture of energy use in the region. However, the authors noted that the model did not accurately project the reduction in coal use in China after 1996-97. The authors in [56] emphasized the importance of holistic evaluation frameworks in the energy sector. They developed a multi-method framework for evaluating digital applications and applied it to conduct a holistic evaluation of aircraft detection lighting systems. The study highlights the need for comprehensive assessments that consider multiple perspectives and impact areas. A generic framework for large-scale literature reviews in the domains of modeling, simulation, and management was proposed in [26]. The authors conducted a comparative analysis of five reviews and identified common elements and differentiating factors. The research demonstrates the importance of systematic and comprehensive literature reviews in informing the development of frameworks. A systematic literature review was performed in [41] to assess the state of art in studies that applied the Heston model in the energy sector. The review highlights the need for comprehensive assessments of modeling approaches to forecast energy generation. Likewise, a literature review was conducted in [31] on sector coupling and its incorporation in energy system models. The review provides a comprehensive understanding of sector coupling and its advantages in terms of decarbonization, flexibility, network optimization, and system efficiency. It emphasizes the need for clear understanding and appropriate tools to model and analyze sector coupling in energy systems.

Consequently, it was discussed in [21] the trend towards developing more comprehensive energy and economic modeling approaches. The authors described various approaches for linking top-down and bottom-up models to achieve a multi-model/sector perspective. The research emphasizes the importance of integrating different modeling approaches to capture the complexities of the energy sector. However, to emphasize the need for comprehensive modeling frameworks that capture the interactions between different sectors, different modeling frameworks used in the analysis of economic growth, technological change, and the environment were compared in [27]. The authors highlighted the use of one-sector aggregate frameworks and multi-sector disaggregated frameworks in energy/climate policy modeling. Similarly, it was presented in [20] a holistic digital twin simulation framework for industrial facilities in the energy sector. The authors emphasized on the importance of integrated modeling and simulation-based optimization to achieve energy and resource efficiency. The research highlights the need for interdisciplinary approaches that consider various subsystems and optimize the overall system's performance. In another comprehensive overview of the literature, an analysis of various aspects of energy demand models, including techniques, prediction accuracy, inputs, energy carrier, sector, temporal horizon, and spatial granularity was carried out [54]. Overall, the literature review highlights the importance of multi-perspective modeling and holistic simulation frameworks in the energy sector. It emphasizes the need for comprehensive assessments, systematic literature reviews, and integrated approaches to capture the complexities and optimize the performance of energy systems.

As such, the energy sector requires a powerful modeling and simulation approach such as the Multi-perspective modeling and holistic simulation approach for understanding and analyzing its complexities. To the best of our knowledge, there has not been a disciplined approach that integrates diverse perspectives of the energy sector such as technological, economic, environmental, and social factors within a single holistic simulation framework. We argue that such a framework is needed to provide valuable insights and support decision-making processes while enhancing the integration of real-world data, and addressing emerging challenges in the energy sector.

3. Conceptual and Operational Framework for Holistic Energy Simulation

We firstly start our methodology by constructing a causal looping diagram the structure of the energy sector, then presents an ontology where various classes that represent major components of ES simulation and their relationships are captured. We later formulate perspectives representing family of energy simulation models using hierarchy of systems specification [58], where models are developed from each perspective and coupled within their respective experimental frames (EF)s for simulation studies. EFs are used to address questions raised by these perspectives from which modeling exercise is being carried out. Following that, multiple models of energy systems are built and assembled within a model repository where instances are retrieved to build a specific energy system. Finally, through an integration mechanism [13], that links models outputs-to-parameters at runtime simulation, we conduct a holistic simulation of an energy system.

3.1. Modeling of the Energy Sector Using a Causal Loop Diagram

Figure 1 presents in details components of energy systems and the relationships that exist between them using a causal loop diagram with major parameters derived from [8, 12, 44], which are close to our work. The CLD starts with the primary sources of electricity that are from renewable and nonrenewable resources.

The conversion limit of the energy depends on the amount of the primary sources as well as other factors such as government policy, industry policy, and technology used for the electricity generation and the fuel processing. The number of installed power plants alongside investment, and environmental conditions are major factors that affect the bulk of electricity generation which produces the price of the electricity in the market based on the cost of electricity. The economic condition is used to estimate the electricity cost and it is based on parameters such as raw material price, equipment price, and investment rate. There is a noticeable loop going from the GDP (Gross Domestic Income) that determines the income of the consumers resulting to electricity demand that affects electricity consumption for the payment of electricity bills, and back to GDP. Fuel processing depends on factors such as conversion limit, technology used, environmental condition, and the available number of plants. Fuel price is function of the amount of fuel being processed and the energy generation cost which affects electricity price as well. Electricity demand is also determined by the number of consumers based on population, electricity efficiency and electricity losses. Finally, electricity consumption is derived from factors such as season (dry or cold season), type of day (working or non-working day), temperature, and consumer behavior. Equations describing the components of the model will be presented in the subsequent sections.

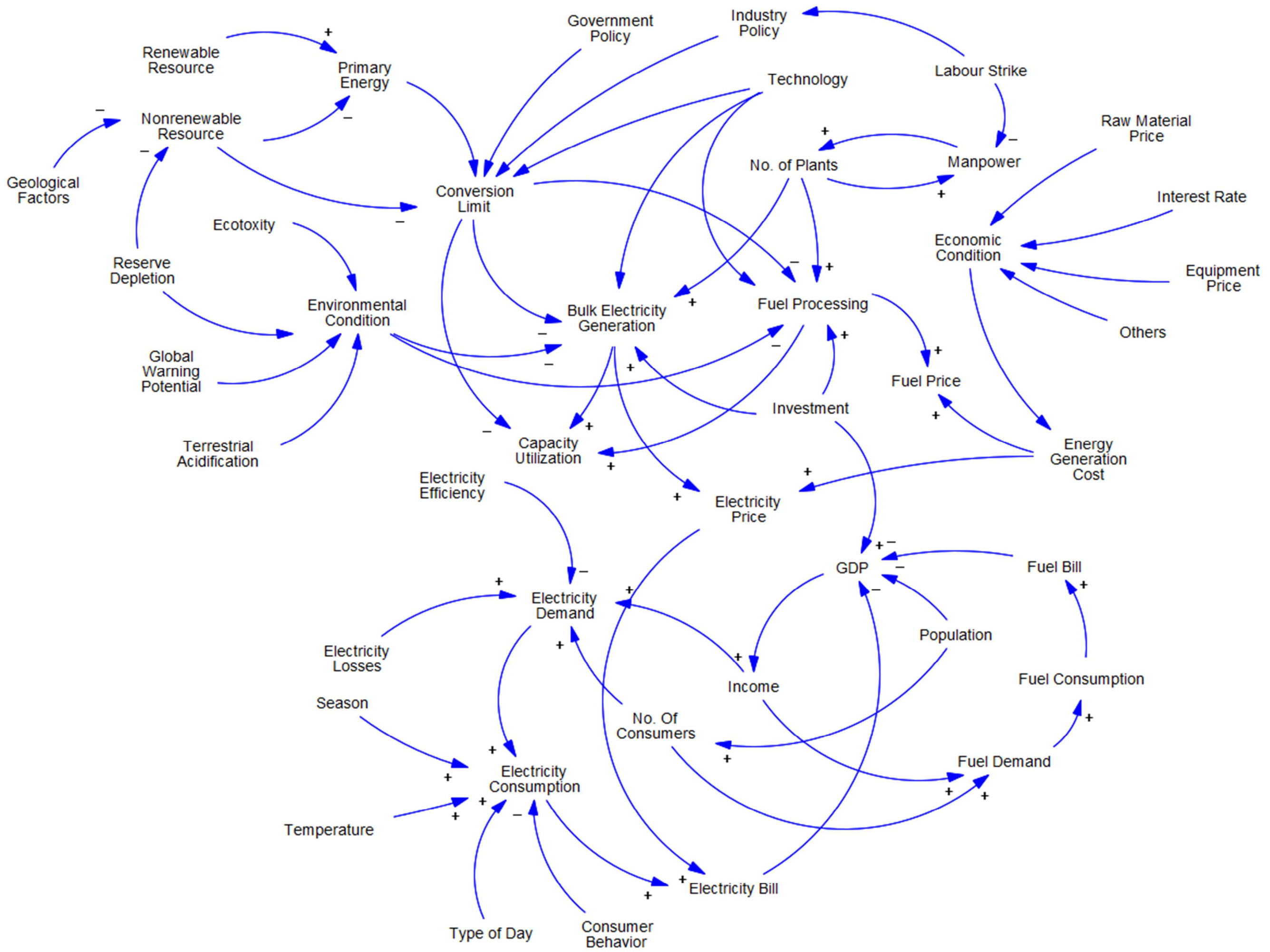

Figure 1. *Electricity Sector explained with a Causal Loop Diagram.*

3.2. Ontological Approach

Energy has become a major resource for a rapid economic, social, and political prosperity of any modern human society, therefore Modeling and Simulation (M&S) related to Energy Systems (ES)s has gained significant research attention these last decades. ES and its multiples ramifications makes it without a doubt a complex system with various aspects interacting with one another through intricate processes. As such, when building the ontology, we review the major contributions in this area by investigating through an extensive literature review existing taxonomies of energy systems M&S as suggested by [19, 35, 46, 50]. Hence, the resulting ontology captures useful knowledge including various classes that represent major building block components and their relationships in the energy simulation domain as an integrated whole. We formally express the ontology using system entity structure (SES) language with links to basic models developed in various formalisms and stored in a model base (MB) repository [59].

SES formalism is a hierarchical knowledge representation for high level ontology construction in terms of decomposition, coupling, and taxonomic relationships among different entities. A decomposition refers to the breaking down of an entity while the coupling refers to its reconstruction. An entity represented by a box has variables written below the box, while an aspect is represented by a single vertical line. A multiple-aspect is also referred to as a composition and is represented by three vertical lines. Specialization is represented with double vertical lines and denotes its taxonomy. The taxonomic relationship provides possible variants of the entity. SES is provided with a set of axioms and an expressive power for modeling and simulation of large and complex systems such as ESs. The ontological analysis of ESs using SES/MB framework relies basically on the multi-perspective approach that serves to develop models at each level of abstraction where different aspects are captured by different views within a complete whole as introduced in [14]. Hence, modeling ESs becomes more practical and richer with deep insights. Classes are built based on agreed-upon concepts in ES simulation domain and serve to document and formalize knowledge while providing notable benefits such as common representation of energy models from different simulation platforms, model retrieval, and model reuse. Figure 2 presents the SES hierarchy of the ontology. Following closely this representation, the first level classification splits Energy System (ES) into a specialization of source of energy as – Non-Renewable Energy, and Renewable Energy - and a multi-aspect, Stakeholders. Non-Renewable Energy is comprised of sources such as oil, coal, nuclear, and natural gas while Renewable source of Energy is composed of sources such as biomass, wind, and solar. Stakeholders in Energy System are among others Generation, Transmission, Distribution, Finance, and Consumption actors. Under the component consumption, we have population, and individual components which to further components such as local, national, regional, and global under special dynamics component that characterizes the scale of the energy consumption. The individual component of consumption also spreads further to components such as commercial, household be it at urban or rural level, transportation, and Industrial entities.

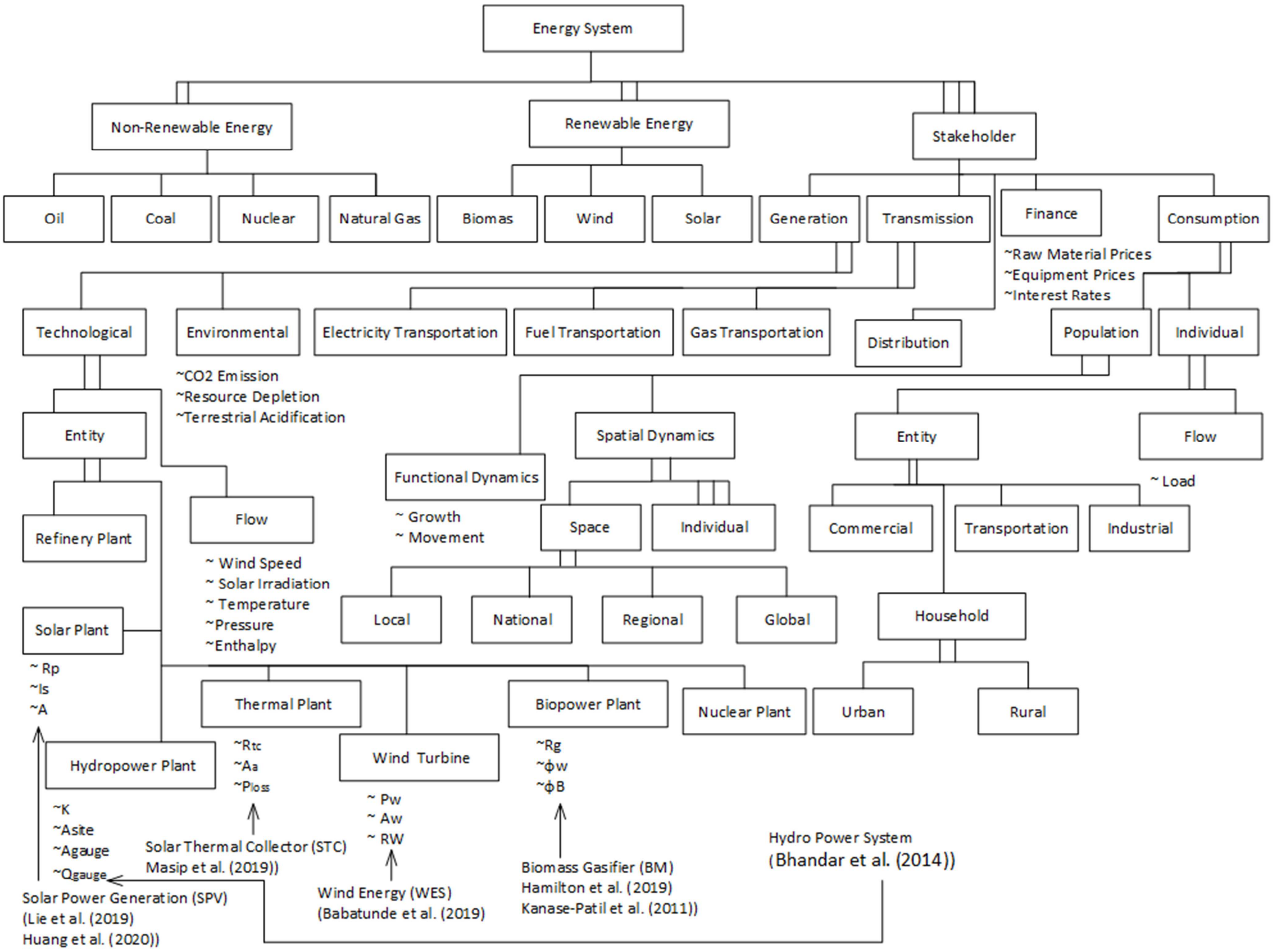

Figure 2. *Ontology for Energy System Modeling and Simulation.*

The ontological specification proceeds furthermore to cover concepts such as technological mode of energy generation that includes components for both renewable and non-renewable energy sources like refinery pant, nuclear plant, thermal plant, solar plant and wind turbine. Entities of the SES tree are expressed as DEVS based parameterized models [13] and stored in the MB repository for model retrieval. Models are organized according to the stratification of abstractions proposed in our framework where they can be mapped into various simulation formalisms such as Discrete Even Simulation (DES), System Dynamics (SD), and Agent Based Modeling (ABM), within a simulation environment like AnyLogic for their execution. Although the authors attempt to cover all existing concepts in energy domain, the goal of the proposed ontology is to establish the main building blocks that will serve as a starting point to be considered in the future energy simulation ontologies.

3.3. Formation of Levels of Abstraction

The proposed ontology encompasses a plethora of problems that are often discussed in the literature for energy simulation. These problems are identified and categorized into five major perspectives as presented in Figure 3, with each one of them representing main concepts in the energy sector while addressing a family of questions that can be addressed through their respective experimental frames. Perspectives are then integrated to form a holistic view of the energy simulation. We consider the following perspectives:

1) Generation perspective: It addresses problems of energy conversion from primary energy sources stored in both renewable and non-renewable natural resources such as fossil fuel, uranium, wind, and solar to its harvesting as electricity and liquid fuels. Models derived from this perspective represent abstractions of aggregated technologies at the unit operation, processing plant and supply chain scale.
2) Transmission perspective: It relates to challenges associated with bulk electricity transmission and the power collapse due to problems such as natural disasters, transmission losses, and wheeling capacity that affects the performance of the overall grid.

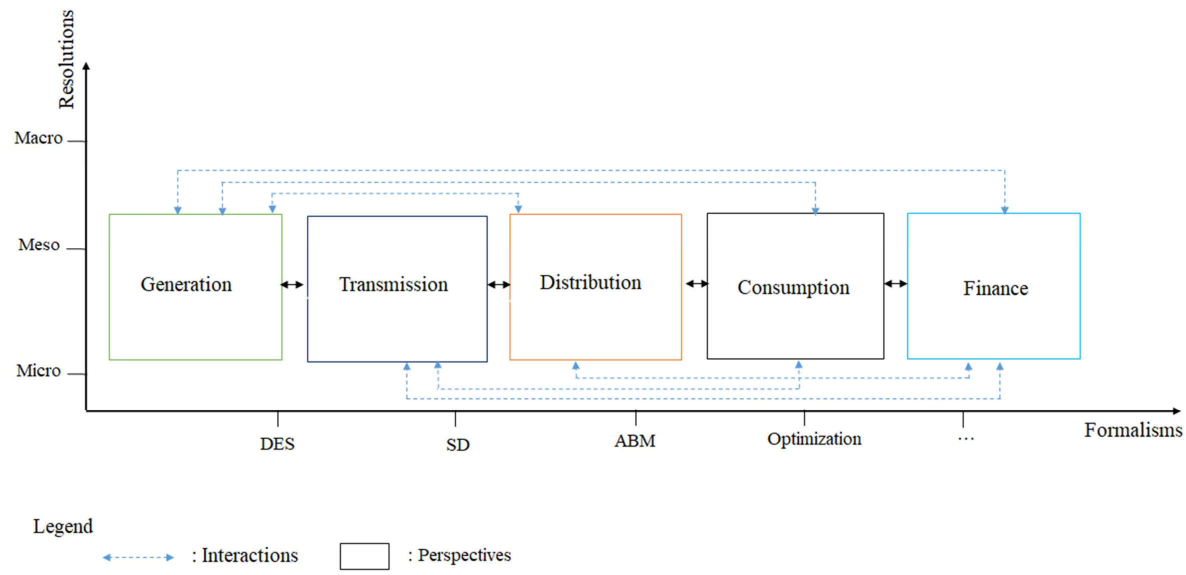

Figure 3. *Multi-perspective framework for energy systems.*

3) Distribution perspective: It concerns with problems affecting reliable electricity supply such as power outage frequency, technical and non- technical losses, and shutdown duration that occurred mostly during electricity distribution and causing customers dissatisfaction of the quality of the service.
4) Consumption perspective: It deals with problems of electricity demand from residential, industry, commercial, and public service based on factors such as population, gross domestic product (GDP), per capital electricity consumption, average income, and electric appliances used.
5) Finance perspective: It addresses the issues of expenses from total cost of production to total revenue, and the leverage points such as cost during transmission, cost during distribution, and electricity tariff amongst others.

The resolutions of the perspectives of the energy systems presented in Figure 3 is done according to the specification of system hierarchy as introduced by [59]. The axis of resolutions includes Micro, Meso, and Macro levels from which the details of modeling of perspectives are carried out while the axis of formalisms reveals formalisms that can be used to model these perspectives and they include among many others DES, SD, and ABM formalisms. The dashed lines between the perspectives (boxes) depicts various interactions that exist between the multiple-perspectives. To achieve a holistic simulation of energy systems, which unifies all the isolated perspectives and their mutual influences within a single simulation model, we follow the integration mechanism introduced in [13] which enables live exchange of information between concurrent simulations in the various perspectives. Section 3.3 provides more details on this integration mechanism.

3.4. Perspectives Integration

Figure 4, is adapted from [52] and depicts the integration mechanism of the energy simulation perspectives as discussed in section 3.2, using the concept of experimental frame. The same system, that is, the energy system, is subject to various objective-driven studies represented by boxes around it. One of the common ways to understanding complex systems is to impose on them multiple design solutions focusing each on different perspective representing the sub-components.

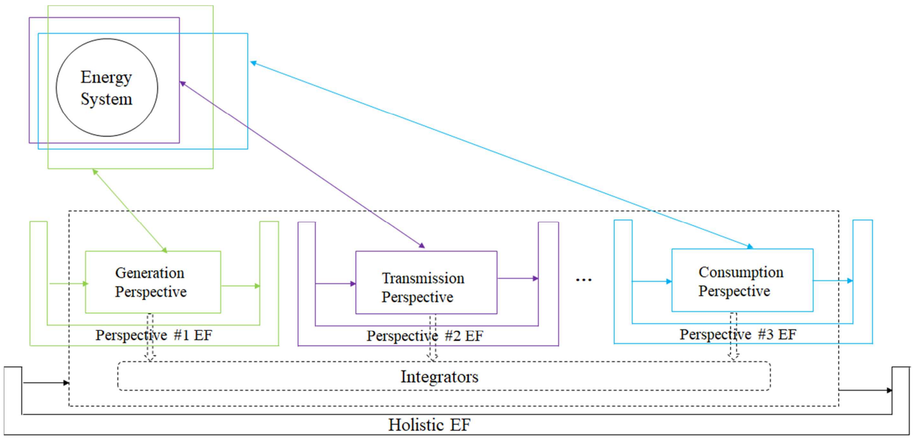

Figure 4. *Holistic Simulation Framework for Energy Systems (Adapted [52]).*

Hence, multi perspective modeling approach helps to overcome the limitations of a single-perspective modeling approach. A fitting approach adopted in this work is the multiple-perspective modeling and holistic simulation (MPM&HS) [13, 52, 53] approach that leads to the specification of different perspective models of the energy system that are bridged together to replicate the overall behavior. Perspectives are likened to the concepts of experimental frames (EFs) introduced by [58] to address any modeling and simulation (M&S) enterprise. In Figure 4, EF represents the set of conditions surrounding the system under scrutiny which drive the objectives of the study. Each model being wrapped up within its own EF is used to run simulations while providing altogether various levels of explanations of the same system under investigation. The integration of models from perspectives is carried out through influences of model-outputs from one perspective to input-parameters of another perspective using integrators at the runtime simulation. The holistic EF is later coupled with the resulting holistic model to derive simulations results that are closer to the reality than when studying these isolated perspectives separately. As a result, a holistic simulation of the energy system which aggregates all the isolated perspectives is achieved as an integrated whole.

4. Application and Results

Having presented the conceptual framework upon which the study is carried out, we provide an explanation of models built according to each of the identified perspectives. Each model studied in isolation produces separate results that are later discussed with the results obtained from the holistic simulation from the integrated perspectives. The different perspectives as well as their integration mechanism are presented in the subsequent sections.

4.1. The Power Sector in Nigeria

This section outlines the main characteristics of the power sector of Nigeria used as a case study, with focus on power generation, power transmission, power distribution, and power consumer actors respectively as described in the modeling section. Electricity generation in Nigeria is managed by twenty-three (23) power generating plants including generation companies (GenCos), independent power providers, and Niger Delta Holding Company - with the capacity of generating 11,165.4 MW of electricity -, that are connected to the national grid [57]. Electricity in Nigeria is produced using hydropower and thermal sources from fossil fuels such as gas that accounts for 86% of the overall electricity generation capacity. Power generation was initially the responsibility for the federal government till the signing of the Electric Power Sector Reform Act (EPSRA) in 2005 that makes the power sector accessible to private investors. The privatization of the power industry has taken over all the power generation sector. Table 1 shows the breakdown of the electricity generation by main producers with their capacity and source of electricity production respectively. The power plant in Niger Delta (5,455MW) tops the production industry followed by IPP (1, 392MW), Kainji Jebba Power Plc (1330MW), Sapele Power Plc (1,020MW), and Egbin Power Plc (1020MW) respectively.

The remaining power producers such as Afam Power Plc (987.2 MW), Ughelli Power Plc (942MW), Shiroro Power Plc (600MW) produce each less than a thousand (100) MW. Nigeria main source of electricity production remains mainly gas followed by hydro. The generated power is far below what is needed to meet the basic needs of household and industrial consumers. Electricity generated by the GenCos is sent to the national grid through the Transmission Company of Nigeria (TCN) and distributed by the Distribution Companies (DisCos) to the end consumers.

Table 1. *Breakdown of main power producers in Nigeria.*

Company (Source)	Capacity (MW)
Kainji Jebba Power Plc (Hydo)	1,330
Ughelli Power Plc (Gas)	942
Sapele Power Plc (Gas)	1,020
Shiroro Power Plc (Hydro)	600
Afam Power Plc (Gas)	987.2
Niger Delta Power Holding Company (Gas)	5,455
IPP's (Gas)	1,392
Egbin Power Plc (Gas)	1,020

4.2. Model of Electricity Generation

The model of electricity generation was developed using System Dynamic (SD) Modeling due to its ability to capture intricate interactions between sub-components of complex systems. SD modeling is based on a stock and flow representation of the existing system with inclusion of feedbacks and delays and has been largely used these last decades for the analysis of the energy sector as witnessed by the works of [8, 12, 33, 39]. The SD model presented in [30] of dispatchable resources was adopted and extended in line with the context of this work using the parametric study of thermodynamic performance of the gas turbine power plant reported in [43]. While most models use ISO rating of the gas turbines with predefined parameter values as given by the manufacturer, it is worth reporting that critical parameter values such as heat capacity of air, ambient temperature, and Mass fraction of air are subject to change during simulation studies. Generally, findings in the literature that address energy generation using gas power plants are based on the following mathematical equations:

The Thermal efficiency η_{th} of the Brayton cycle is given as:

$$\eta_{th} = \frac{\dot{W}net}{Qin} = \frac{\dot{W}t - Wc}{Qin} \quad (1)$$

$$\text{Where } \dot{W}net = \dot{W}t - Wc, \quad (2)$$

is the net power output of the cycle,

Wt is the turbine power output

Wc is the power consumed by the compressor, and

Q_{in} is the rate of the heat added to the cycle.

The power consumed by the compressor is given as:

$$Wc = m_a C_{p,a}(T_{2a} - T_1) \quad (3)$$

Where m_a is the air flow rate, $C_{p,a}$ is the specific heat capacity of the air,

T_{2a} is the actual temperature at the compressor exit and T_1 is the temperature at the inlet of the compressor, the ambient temperature.

The power produced by the turbine is given by:

$$Wt = m_a C_{p,g}(T_3 - T_{4a}) \quad (4)$$

Where $C_{p,g}$ *is* the specific heat capacity of the gases,

T_3 is the turbine entry temperature

T_{4a} is the actual temperature of the gases at the turbine exit.

In this work, we adopt the aforementioned equations and tailor them into our case study while building our model. Figure 5 shows the generation perspective of the electricity sector in SD model that depicts continuous changes taking place within the system using AnyLogic simulation tool [22]. The generator perspective in the model is made up of four state variables – Gas power plant (GPP) Under Construction, Number of Installed GPP, Capital Employed, and Reserves - that represent stock points or accumulations in the system. Each stock has inflow and outflow parameters that control the rates at which the stock increases or decreases respectively in the model over time. For example, the Installed GPP stock has New Capacity Start Up (inflow), Capacity Retirement (outflow), and Capacity Bankruptcy (outflow). Parameters controlling the inflow and outflow of the Installed GPP stock are Construction Delay, and Capacity Lifespan and estimated to be 5 and 20 years respectively in our simulation. The model has many dynamic variables. For example, Desired New Capacity, Wholesale Price, Available Capacity, net profit, adjustment factor, and depletion factors that are calculated in line with equations as specified in [30]. Variable, Desired New Capacity Addition is calculated based on Approved Ratio, and Min Percent to Invest while variable Available Capacity is calculated from the number of Installed GPP, and the Net Power Output Per GPP (Wnet) of the turbine cycle derived from equation (2).

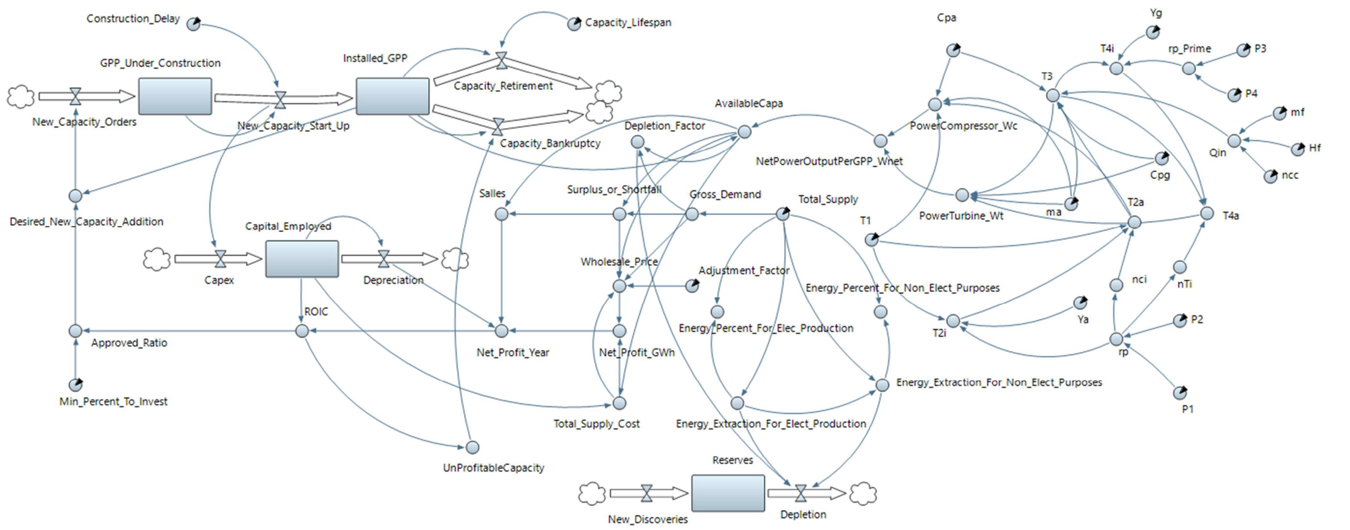

Figure 5. *Power Plant Generation Model.*

Figure 6 shows simulation results of electricity generation capacity. The simulation was run for a time window taken to be 30 years with a model time unit of 1 year = 365 days, the start time was set to be 2020, and stop time 2050. Parameters values such as Exhaust gas temperature, T4 =756.9K, Compressor outlet pressure, P =7.97 bar, and the lower heating value of the fuel, H_f= 49000kJ/kg, are set in line with the work of [43]. The initial value of installed GPP, and GPP under construction are set to be 5, and 1 respectively. Net Power Output from the GPP is calculated based on the installed number of GPP multiply by (times) the available capacity that each GPP can generate as specified in equation (2). As shown in Figure 6, the increase in the number of installed Power Plant from 2020 to 2030 (Figure 6.b) has led to a significant increase of power generation (Figure 6.a) within the same period. However, the electricity generation capacity remained slightly uniform from the period of 2030 to 2050. This is due to a slow increase of installed Power Plant resulting to a slow growth in generation capacity that is triggered by factors such as the approved ratio and the min percent of investment. The latter variables have negatively affected the feedback loop variable, that is the desired for new capacity addition.

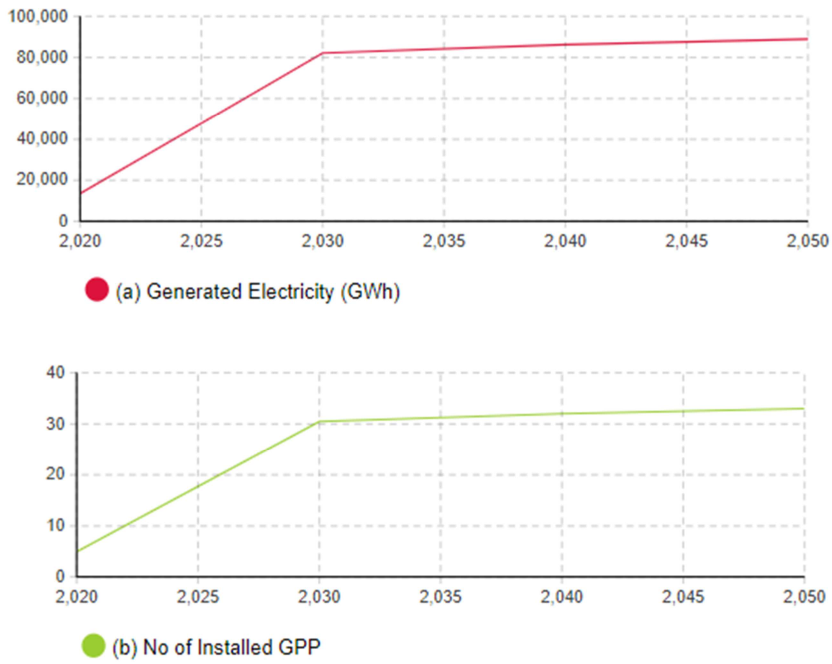

Figure 6. *Electricity Generation Capacity.*

4.3. Model of Electricity Transmission

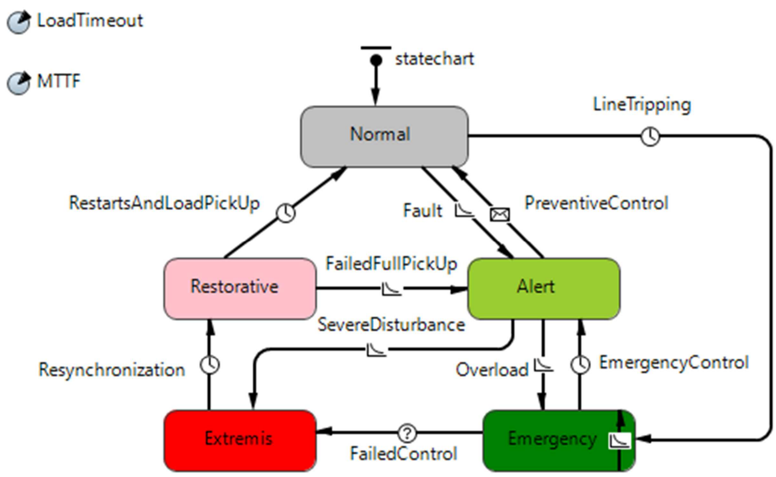

Figure 7. *Electricity Transmission Model.*

The model of the transmission sector is built using Agent-based (AB) modelling, a powerful tool for representing the complexities of electricity transmission line composed of multiple pylons that are linked to one another and have multiple behaviors. Electricity transmission lines are subject to various spatial constraints within a power grid system and challenging to manage for the electricity flows [11]. However, it is argued that physical subsystem such as energy infrastructures, and industrial networks modeled using AB modeling can yield fast understanding. A power system can be in multiple states as described in [25]. Hence, we model the behavior of the electricity transmission towers accordingly in various states such normal, alert, emergency, extremis, and restorative, in the agent-based model as shown in Figure 7. The normal state implies that all system is well functioning with all customer demands met. The alert state implies that even though constraints are still satisfied, the system has been weakened to a point of power overloading. The state changes from alert state to emergency state when a sever disturbance occurs, and if an attempt to solve the disturbance fails the systems goes to extremis state leading to disintegration into multiple sections. The system will go to restorative state if a control measure initiated after total collapse has been successful. Transmission towers are subject to evens such as wind, equipment breakdown, and human factors, that could cause disruption in transmission line. Adopting the work of [2] for the collapse and pull-down analysis of high voltage electricity transmission towers, we present the equation as follows:

$$P_c = 1 - ((1 - P_a) \times ((1 - P_{a-1}) \times (1 - P_{a+1})) \quad (5)$$

where, P_c is the probability of collapse of tower a from all mechanisms,

P_a is the probability of collapse from the direct action of wind

P_{a-1}, and P_{a+1} are the probabilities of collapsed from being pulled down on either side by Neighbors $a-1$ and $a+1$.

Figure 8 shows simulation results of transmission model with the statistics of tower/pylon mainly in three dominant states – green for emergency state; gray for normal state; and red for extremis state - considering the location factors and connection characteristics of collapse as calibrated in [2]. The probabilities are given as $P_a = 0.035$; $P_{a-1} = 0.025$; and $P_{a+1} = 0.015$ respectively. Major causes of repeated breakdown of transmission line in Nigeria are attributed to poor management, and low gas supply resulting to power interruption due to occurrence of faults such as outage, trip, and load shedding. The parameter LoadTimeout representing the time spent from by the system to transition from restorative state to normal state is distributed uniformly from 3 to 7 days, and MTTF (minimum time to failure) is given to be 2 years and an occurring fault is triggered by 1/MTTF.

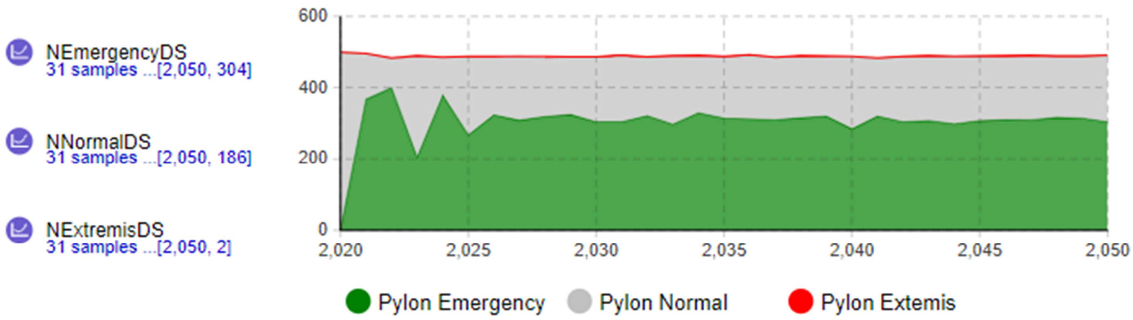

Figure 8. *Electricity Transmission Simulation Result.*

4.4. Model of Electricity Consumption

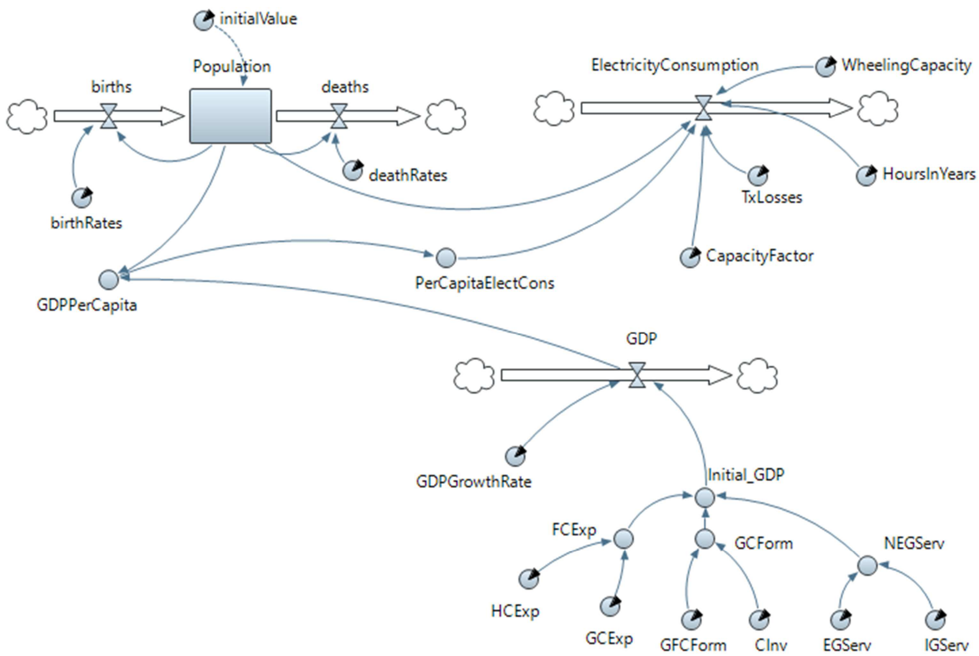

Figure 9. *Nigeria Electricity Consumption Model.*

The consumption model is show in Figure 9 with the estimation of the consumption (MWh) based on major variables such as population, Gross Domestic Product (GDP), and Per Capita Income, as described in [4].

The equation for the Residential Electricity Consumption is given as follows:

$$EC = P(t) \times PCEC \times ER \quad (6)$$

Where:
EC is the electricity consumption in residential sector
P(t) is the population at time 't'
PCEC is the per capita electricity consumption, and
ER is the electrification rate
The per capita electricity consumption is estimated as:

$$PCEC = GDPPC \times \alpha + \beta \quad (7)$$

Where *GDPPC* is the GDP per capita, α = 0.4279, and β = 26.2808.

The GDP by expenditure approach and population growth were adopted from [33] and the equation is given as follows:

GDP by expenditure approach = Final consumption expenditure + Gross capital formation + Net export of goods and services = (Household consumption expenditure + Government consumption expenditure) + (Gross fixed capital formation + Changes in Inventories) + (Export of goods and services – Import of goods and services) (8)

The estimation of the future population growth is given as follows:

$$\text{Population} = \int_{t=1}^{t=31} (birth - death) \quad (9)$$

Where $birth_{t+1} = birthrate_{t+1} \times Population_t$, and $death = averagelifeexpectancy_{t+1} \times Population$

t = 1 is equivalent to year 2020 and t = 31 is equivalent to year 2050.

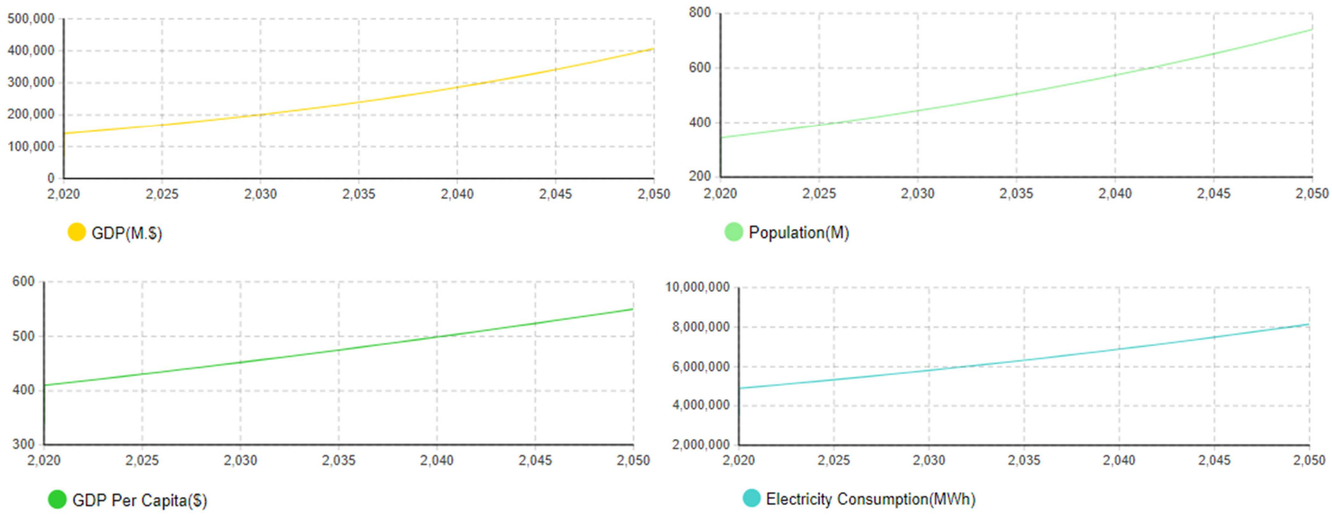

Figure 10. *Electricity Consumption Simulation Results.*

The estimate of initial population, P= 200 million; capacity factor of distribution = 0.6; transmission losses = 0.074; and wheeling capacity = 7500 (MW). The initial GDP of Nigeria was chosen to be the GDP of 2000 and was estimated according to initial values of each variable given in equation (8) using GDP by expenditure approach. Figure 10 shows the results of the simulation from year 2020 to year 2030 of variables GDP (Million) of US $), Population (Million), DGP Per Capita ($), and Electricity Consumption (MWh). It can be observed that in all cases, the curves closely follow the same growth patterns. This resemblance in trends has helped to conclude that as the population keeps increasing at the same time with the GDP, the GDP Per Capita which is calculated as a function of the GDP, also sees a significant increase. Consequently, this results in a considerable increase of electricity consumption within the same simulation period because consumers can afford buying for the electricity. Hence, we observe an increase in the electrification rate in the population.

4.5. Perspectives Integration

The different perspectives of the energy sector are integrated through outputs of some of the models affecting the parameters of the others within the proposed framework. Figure 11 illustrates major influences between outputs and parameters of developed models including models of generation perspective (SD), transmission perspective (AB), and consumption perspective (SD). It is worth noticing that the experimental frame built to experiment with the resulting holistic model provides a more accurate way of model outputs to influence model parameters simultaneously at a run time. Outputs are the influencing variables while parameters are the influenced ones. Hence, we see how perspectives impact each other in deriving closer results to the reality than when they are taken alone in simulation studies.

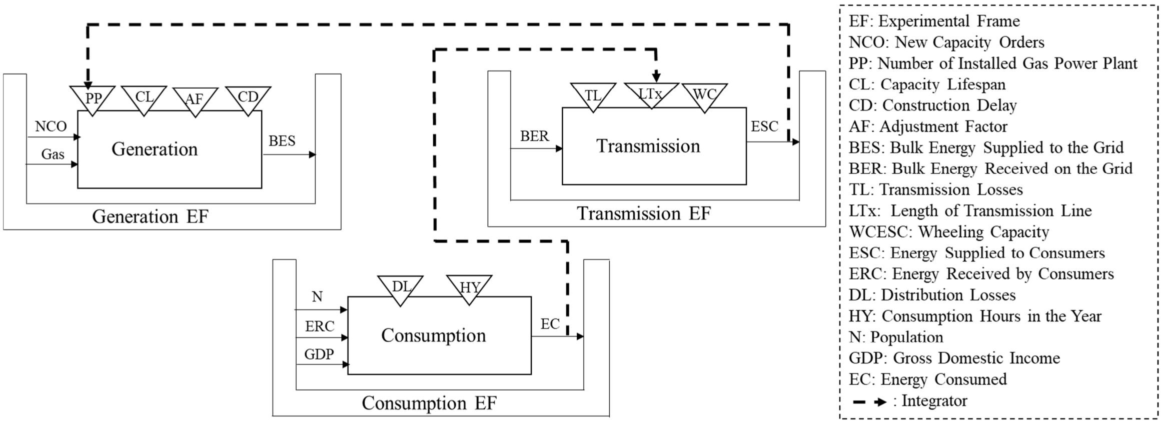

Figure 11. *Integration Through Model Outputs and Parameters.*

The integration of the models is carried using Anylogic Simulation tool such that the Consumption model output *EC* influencing the Transmission parameter *LT*, is done through a statistical function call - *txAndDists.Normal()* – returning the number of transmission towers in the Normal State, *txAndDist* being an array of towers. The returning value is used to determine the appropriate amount of energy to supply (MWh) in the next simulation step. Likewise, the Transmission model output *ESC* that influences the Generation parameter *PP*, is achieved through the function call - *get_Main().Installed_GPP* – that returns the number of installed Gas Power Plant (GPP)s that are currently functioning and supplying the electricity to the grid. This value is used to regulate the required energy based on the specified wheeling capacity while monitoring the causes of transmission lines failures that are due to factors such as overloading, line tripping, and heavy wind. Experiments are run within the simulation window of 30 years and each model is initialized to coincide with the specified period as shown in Figure 12.

Figure 12. *Holistic Simulation Results.*

Electrical towers are modeled as networked agents in an initial "Normal" condition (gray color) across the grid. After being in a brief "Alert" condition (light green), we observe at the top left in Figure 12, a green coloration of some towers that gradually transition to "Emergency" condition. Failed controlled to address this condition lead to "Extremis" condition (red color) resulting into total collapse or pull down. A total power blackout, however does not last long as justified by the tiny red line seen in the Figure. At the middle left of Figure 12, power generation is closely monitored trough output-parameter influence from Transmission model to Generation Model such that the pic of generation remains consistent with the grid wheeling capacity as shown from year 2030 to 2040.

This power over-generation occurs as a result of the increase in new installed power plants, Figure 12 bottom left. We observe another increase from 2040 and above that has to be tackled accordingly. The over-generation is simply redirected to other transmission lines to avoid persistent power line tripping. At the bottom right of Figure 12, we also observe how electricity supplied affects electricity consumption through output-parameter influence from Consumption model to Transmission model as opposed to static simulation discussed earlier. Electricity consumption sharply declines from year 2020 to year 2030 within the same period of repeated power over-generation before picking up from 2030 and above after being stabilized to the normal transmission line capacity. Consequently, we observe at the top right and middle right of Figure 12 a resulting increase in GDP (million dollars), and GDP Per Capita ($).

The key reasons behind the holistic simulation is not only about monitoring the actual output – parameter influence but also to learn the relative impacts of alternative assumptions and government policy interventions in the energy sector as a whole.

5. Discussions

The proposed framework has demonstrated through the case study how multiple levels of explanation can be provided when addressing complex system modeling such as the energy sector using multi-perspective models within multiple experimental frames. Multi-perspective modelling and holistic simulation is a concept commonly used in various fields ranging from healthcare sector to urban transportation to provide a comprehensive understanding of the dynamic interactions within complex systems [14, 51, 55]. Each experimental frame reveals the effects of hidden simulation parameter that cannot be easily identified unless when running simulation of the various perspectives concurrently. The perspectives-related questions are easily answerable following aggregated dynamics of influencing factors from other perspectives. Two approaches– statistic and dynamic integration - are considered in evaluating the simulation results. Most often, in static integration approach of the energy sector, models parameters remain constant throughout the simulation and perspectives such as energy consumption [4], transmission and distribution [33], and generation [43] are studied in isolation. Variation of parameters implies running new experiments on the model to establish the influence of some models outputs on other models parameters. However, in the dynamic integration, parameters of some models are lively influenced at simulation runtime by the outputs of other models through integrators. In this paper, we adopt the latter approach in which case the mutual influence of model output from one perspective to model parameter of another perspective allows to bind the isolated perspectives as an integrated whole in a holistic manner. The simulation models representing the different perspectives of the energy sector such as generation, transmission, and consumptions perspectives were run under two scenarios observation. Firstly, in static simulation, the model parameters were kept constant throughout the simulation study. Secondly, in dynamic simulation, the model parameters were dynamically updated in a live simulation study to depict the interactions between energy components. These parameters include transmission losses, number of installed power plant, wheeling capacity, construction delay, and distribution Losses. The results from the second scenario indicates that simulation parameters with concurrent update of models output to parameter integration fit reasonably with the intended purpose of the model by showing closer results to the reality. Hence, the later scenario is of great interest to decision makers in formulating energy related policies with appropriate impact on the energy sector in Nigeria.

6. Conclusion

A multi-perspective modeling and simulation framework was proposed to holistically study energy systems. The study is rooted in an ontology that is built based on an extensive literature review that captures useful knowledge representing major building block components and their relationships in the energy simulation domain. We have formulated a stratification of level of abstractions - generation, transmission, distribution, consumption, and finance - and shown that each one represents a family of models within its respective experimental frame based on the objectives of the study. While the ontology is expressed using the system entity structure, the implementation of the abstractions is carried out through diverse formalisms such as system dynamics modeling, and agent based modeling, and the resulting simulation models are stored in a model based repository within the AnyLogic simulation environment. In most findings, these perspectives are studies in isolation while in this work, they are coupled together through model output-to-parameters in a live simulation showcasing the interactions that exist between these components in reality. This is an important contribution that supports a comprehensive analysis of the energy systems simulation. The running example of the Nigerian electricity sector was used to show how the proposed framework works. The holistic study showed the following results as depicted in Figure 12:

1) Electrical pylons/towers are modeled as 500 networked agents in a “Normal” (gray color) condition initially across the grid.
2) We observe a live green coloration depicting “Emergency” pylons occurrence mainly due to factors such as over-generation, over-loading, and severe disturbance that can lead to grid collapse and pull down as depicted by the red color, “Extremis” condition.
3) Extremis condition cause a total power blackout but doesn’t last long, this is shown by the tiny red line in the Figure.

4) When a line tripping occurs due to over-generation, the power generation is immediately readjusted to its maximum generation capacity supported by the wheeling capacity. This is seen in the Figure where the increase from year 2020 – 2030 is stabilized from year 2030 – 2040 before another over-generation occurs again and the same mechanism is applied. The over-generation is simply redirected to other transmission lines to avoid persistent power line tripping.
5) It is also worth noticing how power grid performance lively affects electricity consumption as opposed to static simulation discussed earlier.
6) We see an unstable power consumption around year 2020 – 2030 due to the occurrence of the “Emergency” pylons within that same period.

It is observed from this study that not many holistic simulation research activities were carried out on the Nigerian electricity sector. Hence, in the future we suggest to expand each of the developed models toward a complete global model that will expose all the hidden and intertwined socio-economic and political factors of the Nigeria electricity sector. It is hoped that this approach will be generalized and used beyond the current work to explore holistic studies of other complex systems as well.

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Conflicts of Interest

The authors declare no conflicts of interest.

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