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SYSTEM DYNAMICS MODELLING FOR ENERGY PLANNING AND CARBON-DIOXIDE EMISSIONS: A CASE OF THE NIGERIAN POWER SECTOR

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ABSTRACT

Energy is essential to supporting our daily activities; it is a main driver of economic development and carbon dioxide (CO_2) emissions. Due to associated complexities and uncertainties, decision makers and energy planners are facing increased pressure to effectively address energy related challenges, including greenhouse gas (GHG) reduction, in the sector. The study seeks to bridge the electricity supply-demand gap by developing a system dynamics (SD) model for the Nigerian power sector (NPS) in its long term performance, 2010 to 2050. Using the developed SD model, the following were evaluated: i) the contribution of the Mambilla hydropower (MMPH) upon its completion at the horizon of 2024; ii) the contributions of renewable and non-renewable energy capacities under-construction; and iii) the carbon dioxide (CO_2) equivalents emissions of the contributions. These were done under six policy scenarios. The factors assessed were the: 1) Transmission losses (Tx); 2) Time to Adjust Capacity (TAC); 3) Population Growth Rate (PGR); and 4) Capacities under construction. Thus, results showed that the completion of existing project and the MMPH would make the NPS 71% energy secured at the end of simulation period (2050). This was achieved as a result of Tx reduced by 0.5%, earlier TAC (15years), and a PGR of 2%. Results also revealed a paradigm shift in CO_2 reduction in the planning process considered by the study in contrast to the existing generations. It was advocated from the study that for the NPS to be totally out of energy poverty, it must decentralize the energy generation means and review its rural electrification policy. Emphasis should be put on harnessing grass root energy resources and more renewable energy in its energy mix. Also, capability of SD is affirmed by properly capturing feedbacks, delays, and other complexities in the NPS.

Keywords: system dynamics, Carbon dioxide, Nigerian power sector, Mambilla hydropower.

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ABBREVIATION AND UNITS

BAU	Business as Usual
BU	Business Unit
CFW	Conceptual Framework
CLD	Causal Loop Diagram
CO_2	Carbon dioxide
DISCOS	Distribution Companies
ECC	Electricity Consumption per capita
ECN	Electric Corporation of Nigeria
EDG	Electricity demand Gap
EPSRA	Electric Power Sector Reform Act
FB	Feed Back
FGN	Federal Government of Nigeria
FMP	Federal Ministry Power
GDP	Gross Domestic Product
GENCOS	Generation Companies
GHG	Greenhouse gas
HP	Hydropower
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IPCC	Inter-governmental Panel on Climate Change
MMPH	Mambilla Hydropower

MYTO	Multi Year Tariff Order 2.0
NCC	National Control Center
NDA	Niger Dam Authority
NEP	National Energy Policy
NEPA	National Electric Power Authority
NEPP	National Electric Power Policy
NERC	Nigeria Electricity Regulatory Commission
NESP	Nigerian Energy Support Program
NG	Natural Gas
NPS	Nigeria Power Sector
NPSI	Nigeria Power Sector Investment
NREEEP	National Renewable Energy and Energy Efficiency Policy
PCE	Per Capita Electricity
PGR	Population Growth Rate
PHCN	Power Holding Company of Nigeria
RE	Renewable Energy
REA	Rural Electrification Agency
SD	System Dynamics
SFD	Stock and Flow Diagram
STD	Stock and Flow Diagram
TAC	Time to Adjust Capacity
TED	Total Electricity Distributed
TEG	Total Electricity Generated

Tx	Transmission losses

Units

CO_2 e	Carbon dioxide equivalent
GW	Gigawatt
GWh	Gigawatt-hour
KWh	Kilowatt-hour
KWh/capita	Kilowatt-hour per capita
KWh/m^2/Day	Kilowatt-hour per square meter per day
M	Meter
Mt	Milliontonne
Mte	Milliontonne
MW	Megawatt
Pe/yr.	People per year
TWh	Terawatt-hour
USD/ca.	US Dollar per Capita
USD/yr.	US Dollar per year

CHAPTER ONE

INTRODUCTION

1.1 Background of study

Global population growth and industrialization will result in increased demand for energy resources and a need to balance energy supply and demand in order to achieve a well-structured and sustainable energy mix. This will compel policy and decision makers to respond more effectively to a number of energy-related crises, such as inconsistent power supply, conflicts in meeting various aspects of energy needs, as well as greenhouse gas (GHG) emissions.

The International Energy Agency (IEA) projects a 70% increase in global energy demand and a corresponding 60% in GHG emissions compared with 2011 data by extending the current trends to the year 2050. This means and upcoming devastating and harmful consequences related to climate change. Therefore, measures to constrain the expected rise in temperature above 2^oC is critically underway which emphasis is laid more on the energy sector (Moret et al., 2015).

The energy sector is a major contributor to GHG emissions (Kerem & Hekimo, 2013). The choice of an alternative energy source goes a long way in mitigating GHG emissions and unfavorable impacts climate change (Robalino-lópez et al., 2014). Hydropower and other renewable energy sources are known as key players in the world's bid to both power up and fight the emissions that cause climate change, thus generating clean energy with very little or no emissions of carbon dioxide (CO_2) (Aslani et al., 2014).

Scientists reported that earth reached its highest temperature in record in 2016 passing the previous record three consecutive years (Mooney, 2017). It is the first time in the industrialized era that global temperatures are approximately 1.2 degree Celsius above pre-industrial levels. This phenomenon is being driven by increasing levels of CO_2 and other GHGs, mainly caused by human activities. The main consequences of climate change include melting glaciers, drought, extreme weather events, heat waves, thereby, stressing water bodies and declining river flow and causing discomfort to humans. Hence, this has impeded capacity to most hydropower plants and other renewable energy sources to generate electricity to their full capacity.

Climate change impacts has led the way to difficulties in managing and operating of hydropower facilities and other energy sources. This has been main concern to researchers and decision makers. In these regards, future hydropower dams have to be developed with better technology and with improved research, compelling countries to work together in an integrated water management approach in times of water stress and emerging climate change issues.

The projected (ambient) temperature rise during the 21st century is expected to increase the energy demand for cooling and other activities. In such, hydroelectricity and other renewable energy (RE) sources remain the important sources of power in Nigeria and West Africa that could be mostly impacted by climate change.

Nigeria, the most populous African nation, with a population of over 180 million in 2015 (CNN, 2017), still struggles to meet the supply of and demand for electricity, despite great natural resources and the abundance of rivers. The Nigerian Power Sector (NPS) is yet to harness the full available energy potential from hydropower, as only one-quarter of the grid electricity generation by 2015 was from hydropower. The remaining was from gas fueled power plant, making the Nigerian energy mix unreliable and prawn to frequent collapse. Also, this sector is more vulnerable and is subjected to the devastating impacts of climate change. Thus, there is a need for the national energy mix to incorporate other forms of energy generation sources. On March 31st, 2016, the nation suffered a nationwide blackout as the national grid totally collapsed due to sabotage of natural gas which is the major source (3/4) of the electricity generation in Nigeria. To further stress this fact, the nation has been experiencing epileptic power supply, recording even more blackouts, a clear indication of insufficient electricity supply. This has led to the relocation of industries and companies due to the high cost of generating energy for the production of goods and services.

Nigeria could be energy self-sufficient in a sustainable and reliable fashion if proper planning is considered in her energy sector taking into account the future impacts of climate change. In this study, a system dynamic (SD) model is proposed to identify and capture the numerous feedback (FB) loops in the Nigerian power sector. These FBs were then used to investigate the impacts of the future Mambilla hydropower in meeting energy supply-demand needs. The model also considered other proposed RE and non-RE projects in the Nigerian energy mix. This project seeks to determine to what extent local and national fossil fuel and the subsequent CO_2 emissions would be cut down and what would be the impact on federal economy.

1.2 Problem statement

The Federal Government of Nigeria (FGN) has been (1972-2005) solely responsible for the regulation, operation, and investment in the domestic power sector (NESP, 2015b) through the National Electric Power Authority (NEPA). The Power Sector Reform Act was enacted in 2005 transferring the public monopoly of NEPA to Power Holding Company of Nigeria (PHCN), which was unbundled into eighteen (18) Business Units (BU): eleven (11) distribution companies, six (6) generation companies, and one (1) transmission company (Nigeria Electricity System Operator, 2016). The act was to guide the electric sector in its operations with the hope that the Nigerian electricity system would improve (Momodu A. S., 2012).

Despite the deregulation and restructuring with the goal to privatize the power sector, around 85% of Nigerians consumed energy of which 99.3 Mtoe annually came from biofuel and waste. This means that biofuels and waste cover about 98% of the energy demand in the residential sector (NESP, 2015b), accounting for the rapid change in the country's vegetation loss and the increase in desertification. This explains the reduction in carbon sinks, which enhances global warming. The over-exploitation of the country's vegetation will be compounded as the rural and urban population increases in line with the forecast rate of 2.5% per annum (World Bank, 2014).

Nigeria has an installed capacity of 13.40 GW, only 6.20 GW of which were operational as of 2014. Of these, only 3 GW to 4.5 GW are actually being generated due to unavailability of gas. Therefore, 2.7 GW were lost due to gas constraints, breakdowns, water shortages, and other grid constraints. This has led to an acute shortage of power across the country (NESP, 2015b). Unfortunately, the current reality does not meet the public expectations. As a consequence, only 40% of the population was connected to the national grid for their electricity supply and they were experiencing more blackouts.

Electricity deficiency in the Nigerian power sector can be attributed to the constraints in the rapid development and diffusion of hydropower technologies for the exploitation and utilization of renewable energy resources in the country. Also, the absence of market, the lack of appropriate policy, regulatory, and institutional framework to stimulate demand and attract investors, and the overdependence on electricity generated from gas fueled power plant contribute to the deficiency. Therefore, Nigeria should consider the enormous potential of its renewable energy resources in its drive to match electricity with demand and achieve the Intended Nationally Development

Contribution (INDC) goals and Sustainable Development Goals number seven (SDGs7). It is important for Nigeria to invest in critical areas of hydropower dam construction, other RE projects, and deployment.

Thus, the Nigerian future electricity demand and consumption, as illustrated in Fig. 1.2, shows a clear deficiency in electricity supply.

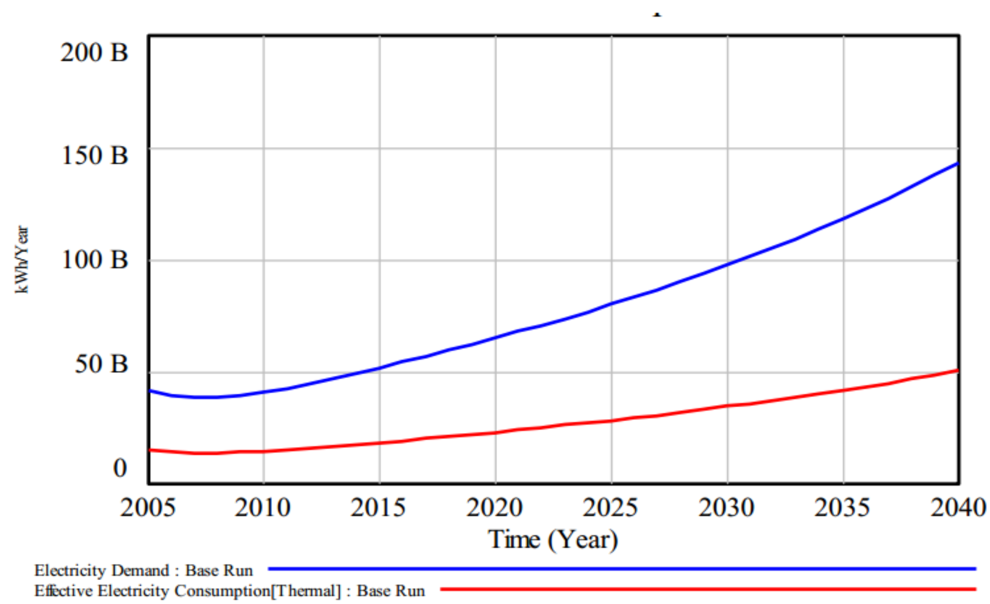


Figure 1.2. Electricity Demand and Effective Consumption. (Momodu, 2012).

A significant share of electricity demand remains unmet. Hence, this research will investigate how electricity projects under construction would improve the Nigerian life style and quality under various policy scenarios and estimates CO_2 emissions from the various generating plants considering its fuel type. Thus, how the impacts on future climate change could be mitigated.

1.3 Research questions

System dynamics modelling approach in a STELLA software was used to develop an SD model for the Nigerian electricity sector. This was utilized for subsequence analysis in order to find logical outcomes. On this note, the developed model would find out:

i. The effective role of SD model in capturing the dynamic behaviors in the Nigerian electricity system

ii. If supply-demand gap in the Nigeria power sector will be met upon the completion of Mambilla dam by 2024 and other electrification projects under construction; and

iii. To what extent will the CO_2 emissions be reduced, considering the use of renewable energy sources for electricity generation?

1.4 Research hypothesis

Nigeria could be energy sufficient at the horizon of 2024 upon completion of the Mambilla Dam, and development of other electrification RE and non-RE projects that are under construction, considering her population growth rate.

1.4.1 Principal objective

The main objective of this study is to investigate how Nigeria can use hydroelectric power and completion of electrification projects under construction to be energy secured and reduce the supply-demand gap of electricity by applying a system dynamics modeling approach to energy planning.

1.4.2 Specific objectives

1. Develop system dynamics model of the Nigerian electricity system;
2. Evaluate the Mambilla hydropower dam (3050MW), other electrification projects role in electricity supply-demand gap's long term effect (2010 – 2050); and
3. Estimate their role in reducing greenhouse gas emissions using the developed model.

1.5 Significance of the study

The need to embark on this study was informed as a result of electricity supply inadequacy in the Nigerian Power Sector (NPS). This, at a rate that does not complement its teeming population growth and economic development. Hitherto, most of the electrification projects, including infrastructures, were stalled and unduly prolonged; some were in there dilapidating stage. The need for Nigerian policy makers to be informed, of the contributions of ongoing electrification projects in NPS and their respective GHG emissions and subsequent contributions in "lighting up" Nigeria, need to be understood.

1.6 Research boundary and limitations

The study considered the Nigerian power sector, population growth, and estimation of GHG emissions. Electricity supply-demand gap was investigated and electrification projects under construction were surveyed. Thus, the study was not only limited to electricity generation in the Nigerian power sector, but was also based on electricity data obtained from secondary sources. Transmission and distribution aspect of power were not considered. Also, financial implication of investing in both renewable and non-renewable energy resources in the sector energy planning were not included. Moreover, the electrification projects that were not deployed for construction "pilot stage" with proposed date of completion were not considered.

1.7 Structure of the study

The thesis is structured into five chapters.

Chapter one involves the background, research questions, research hypothesis, research objectives, significant of study, and the study's boundary and limitations.

Chapter two explains the theoretical and empirical review by describing the concepts of energy planning, various theories and techniques, energy models, system dynamics modelling approach, and SD principles in relation to climate change.

Chapter three elucidates the methodology in the context of the study area, phases of legislation in the NPS from inception till date, the conceptual and mathematical framework of study, the process of data acquisition, and the model overview, *viz*., causal loop diagram, stocks, and flow diagram of the system understudy.

Chapter four presents the results of the research and the subsequent discussions. It also provides the findings of the generated and distributed electricity at different scenarios, illustrating the demand gap, and GHG emissions.

Finally, **Chapter five** concludes the thesis with the likely policy implications and recommendations which further assist researchers, policy makers, privates and public institutions, and energy investors interested in financing the NPS.

CHAPTER TWO

LITERATURE REVIEW

This chapter explains the theoretical and systematic review by describing the concepts of energy planning, theories, techniques, energy models, system dynamics modelling approach and principles, it relationship with climate change and the Nigerian energy policies. These reviews were used to structure the research approach to energy planning in the conceptual context of NPS.

2.1 Energy Planning

It is a fact that energy cuts across social, economic, and security interest, as well as climate and environmental concerns, making it one of the most important commodity for development. Therefore, energy planning should be prioritized for any sovereign nation or state in order to attain sustainable development and social wellbeing (Moumouni et al, 2014).

From the review of different literature, a general meaning for energy planning could be attributed to developing a long-term energy policy to help guide the future activities of local, national, and regional energy systems. Different stake holders including the government, private organizations, and individuals are to be involved with energy planning.

Energy planning is often conducted using integrated approaches that consider both provision of energy in terms of electricity generation, supplies, and the role of energy efficiency in the aspect of demand side management in reducing electricity demands (Vlachos et al., 2007). Outcomes of population growth and economic development is always a major aspect when undergoing energy planning activities, irrespective of the approach involved.

(Kaya & Kahraman, 2011) considered energy planning as a complex issue, which requires processes of developing long-term policies to guide the future of a local, regional, national, and global energy system in order to meet energy demands in the best desirable manner.

2.1.1 The Planning Concept

Planning is often thought of how to do, what time, when, and at what cost. It could be as simple as arranging our daily activities, while on the other hand, it could be complex and dynamic. Planning processes could be simple or complex/dynamic in scheduling. Either way it takes, simple or complex (Rad, 2011), planning follows a series of procedure involving steps which are linked to other phases of processes to achieve one or more goals in the future.

Planning concepts, models, and techniques have been explained and defined by many authors dated back in the 1970s.

(Ozbekhan, 1970) described the evolution of planning as human attempt to develop tools to overcome or solve problems. He pointed out that these problems were integrated with the human environment which were found in large, integrated, inter and intra-active, complex and dynamic systems, forming the overall behavior of the system. Thus, planning could be difficult to understand. Ozbekhan therefore, referred to planning as a problem solving approach and a tool which helps to deal with such problem.

(Foell, 1985) illustrated an analytical framework to planning. He explained the framework in a form of analysis and planning activities, dividing it into two parts, *i.e.*, i) the descriptive assessment and analysis and ii) the decision-oriented analysis and planning. Foell described the former as the most basic initial information gathering and descriptive activities to planning and the latter as consisting of more focused analysis pointing towards a set of activities, specific decisions, implementation efforts, project selection, and strongly dependent upon an active institution. Such example could include electricity generation expansion plan.

Furthermore, Foell’s descriptive assessment can be explained by many assessments carried out by some specific organization, *i.e.*, World Bank projects. This assessment and research project created the basics for information and data sources for many countries, especially emerging nations. Energy planning in some developing countries are yet to make transition from descriptive to the decision-oriented form of planning. Hence, this set back could be due to the preoccupation of the events of surveys and data acquisition activities, thus making many analysis and planning efforts abortive, unachievable, and difficult.

Foell further identified planning steps that helps to focus the process of analytical framework of planning:

a) Identification of underlying problem, with a clear statement of objective to the underlying problem;

b) Identification of alternative and better policies and laws in response to the underlying problems and objectives;
c) Determination of the consequences of alternatives, due to complexity of the planning models and energy system, which may require the use existing models or development of new models;
d) Examination of the consequences based upon a variety of criteria and values; and
e) Evaluation and development of a plan and action agenda, obtaining results for appropriate implementation by policy makers.

The aforementioned processes outlined might seems abstract for practical application. But it is valuable for focusing the planning process and avoiding unnecessary and costly data collection and analysis.

(Rad, 2011), further referred to planning as a tool and a guide to practice in anticipated decision making, forming an aspect in the total decision process of a system, and events that are yet to occur but envisioned for a specified purpose. This further buttress by Hurley, who defined planning as a decision made in advance, considering various alternatives, such as objectives, procedures, and programs to be selected among alternatives.

Making a brief summary from the above reviews, planning can therefore, be described as the design of a desired future which involve simple or dynamic, but effective processes of bringing it to reality. In this regards, planning is a systematic process of establishing a need and working out the best way to meet the need.

In this research, planning would be considered in the aspect of energy planning, considering the fact that process is complex and multi-facet. Therefore, the study seeks to employ a system approach, so as to capture the complexities in electricity planning process, considering its long term. These would be applied to the Nigerian electricity sector.

2.1.2 Planning theory

Various approaches have been undertaken to form the general theory of planning through linking planning with different fields which turned out to be confusing. As such, planning theory should be clear enough, since any planning activity is about achieving desired goal(s) in the future, through some steps and within a specified period of time. Therefore, the concept of planning theory should create a better understanding on the approach to planning applied on different disciplines. Thus, planning follows some steps which are fundamental to the theoretical framework of this research.

(Hudson, 1979) attempted to develop new perspectives to the field of planning theory. He classified planning theory into five classes, which were identified as: Synoptic, Incremental, Transactive, Advocatory, and Radical (SITAR) planning.

a) **Synoptic planning** views problems from the system view point, thereby adopting conceptual and mathematical models to solving it. It is heavily dependent on numbers of the quantitative analysis. Hence, synoptic planning requires large data difficult to interpret. It is obvious that data required by synoptic planning are difficult to utilize by emerging nations due to the lack of a good database. However, it is believed that synoptic planning is considered more robust in the scope of problems it addresses and its capacity to tolerate diverse form of challenging conditions (Boyne et al; 2004);
b) **Incremental planning** is based on the accomplishment of public policy through decentralized processes in a liberalized market and a democratic economy. According to (Lindblom, 1959), incremental planning is comprehensive for decision making. In this, policy is made dynamic open to re-amendment. Thereby, it is easier to avoid unintentional mistakes and inaccuracy that precede changes in policy and is capable of being predictive;
c) **Transactive planning**, this approach is more focused on the experience of people’s lives. It also focuses on the challenges and the policy issues that need to be solved or addressed. This planning theory deals with policy that affects inhabitants at the grass root in their various communities. Unlike synoptic planning, Transactive planning approach is a “no data intensive” and does not requires rigorous field surveys and data analysis. Thus, it helps people to take more control over their social processes that addresses their welfare by focusing on interpersonal interaction and mutual dialogue. It also involves decentralization process of learning which enables people to take control of their local resources. This planning theory would be better adapted to emerging nations;
d) **Advocative planning**, this aims at developing more plans rather than a single plan. Hence, it is a pluralistic form of planning theory, which encourages selection among various competing plans. In this protect, the interest of the poor in the society or community groups against the

strong and established power of businesses and government. This advocates and encourages citizen partnership in the planning process, thereby formulation of future policies from smaller interest groups out to larger social groups;

e) **Radical planning,** this is a planning process that is more action-oriented and more rooted in civil society rather than the state. Hence, it is often in opposition to the state and encourages social movements to define the right to housing, socially and ecologically sustainable development. Radical planning could be sometimes achieved through industrial action from the civil society, as reported by (Friedmann, 2008).

The above defined planning theories are sufficient to map various challenges that planners encounter. It is suggested that a hybrid application, *i.e*., the ability to mix different approaches, of these theories would be better preferred to respond to diversities of challenges and complex situations faced by planners. To this end, planning can be attributed to policymakers, who are not directly involved in all the phases of planning which includes: establishment of criteria for generating, identification, and choosing among alternatives which are based on decision.

Planning theory is simply the general process of planning, incorporating specific planning processes which is identified or defined by planning objectives, purposes, and decisions (Rad, 2011a).

2.2 The concepts of energy planning and climate change

This section stresses the need, advocating on sustainable energy planning concept, which can support the implementation of renewable energy resource in emerging nation's energy mix. It also emphasizes the subsistence and development of alternative sources in relation to the economy and environment.

Some emerging nations with abundant fossil fuel resources have been emphasizing on investments in oil, coal, and natural gas exploration activities (Rikke et al., 2014). This mean their energy infrastructure basically would depend on fossil fuel resources for its survival. Thereby giving priority to fossil fuel utilization in its energy policy, this was wrongly regarded as a key element to alleviate energy poverty. In this view, Nigeria that heavily relies on fossil fuel resources has been experiencing various energy turmoil and will continue to face energy insecurity in the future.

At the same time, energy policies and planning concept and tools in supporting renewable resources in the Nigerian energy mix are weak and not really legislated to proper deployment.

Planning of future energy strategies has been and is still often considered by decision makers at the local, state or Regional and national levels. These allow government at different levels make timely an informed decision about managing energy supply and demand, including resources. Energy planning is particularly valuable given the long operating life of energy systems, which informs the possibilities of evaluation of near term decisions in relation to its long-term implications for the economy, the environment, and the society. In the long run, energy planning supports and encourages efficient and wise investment decisions.

According to the International Atomic Energy Agency (IAEA), energy planning provides decision makers with the following: i) an identification of options, this helps investors in energy resources assess strength and weakness of various energy opportunities; ii) a comparative means of alternatives, this involves cost analysis of different options and scenarios of energy investment opportunities; iii) an exploration of constrains, this has to do with the analyses with regard to the limitations of existing or future frameworks, in terms of policy, national agenda, and financial commitment; iv) a possibility of outcomes' evaluation, deals with energy planning estimate of potentials for success over a short-term and a long-term period.

Therefore, IAEA refers to energy planning as a national asset, which when comprehensively done has the capacity to improve countries' ability to anticipate and respond to rapid changes and new issues emerging in the energy sector.

During Energy planning, energy technology based on solar energy (photovoltaic and thermal), wind energy, hydropower, biomass, combine heat and power (CHP) are among the most popular energy technologies and also known for its environmental-friendly ability, therefore should be prioritized in the planning process.

(Kaya & Kahraman, 2011) & (Rad, 2011b) claimed that during energy planning processes, the technical, economic, environmental, and social attributes should be taken into consideration.

Table 2.2 shows the criteria for assessing the sustainability of an energy planning process, thereby, showing details of the main areas to be considered in energy planning processes.

Table 2.2. List of evaluation criteria on energy planning issues. Adopted from (Kaya & Kahraman, 2011).

. **Aspect of Sustainability**	**Criteria to be assessed**
Technical	Efficiency *
	Primary energy ration
	Safety
	Reliability
	Maturity *
Economic	Investment cost *
	Operation and maintenance cost *
	Fuel cost and electric cost
	Payback period
	Service life
	Equivalent annual cost
	Others
Environmental	NO_x emission *
	CH_4 emission *
	CO_2 emission *
	CO emission
	SO_2 emission
	Particulate emission
	Land use
	Non methane volatile compound
	Others
Social	Social acceptability *
	Job Creation *
	Social benefit
	Others

*Frequently considered during energy planning process

2.2.1 Climate impacts on energy systems

This section presents an overview of how energy sector might be impacted by climate change, vice-versa, and also discusses means to proper adaptation suitable for the sector

Energy services are the main ingredients to economic development and growth. Despite this, they could be prone to diverse disaster due to climate change. Consequences of climate change will make the entire energy supply chain more vulnerable to climate variability and extreme conditions that can affect energy resources, supply, and demand. The projected changes according to the International Panel on Climate Change (IPCC) will increase energy systems' vulnerability, thus a need to adapt to the changing conditions.

Climate change could also have direct effect on energy endowment, such as wind, temperature, water, etc., and energy infrastructures, such as energy transmission line and distribution devices. It could also have an indirect effect through economic sector (Ebinger & Vergara, 2014). As a results, 70% of GHG emissions comes from fossil fuel combustion during electricity generation in industry, buildings, and transport. These emissions were projected to rise (Ebinger & Vergara, 2014). Thus, the energy sector is regarded as one of the main driver of GHG emissions and the global warming phenomenon.

Conventional forms of energy sources like coal, natural gas, and oil are known for their large share and increasing source of GHG emissions (these include, but not limited to carbon dioxide CO_2, carbon monoxide CO, nitrous oxides NO_x, methane CH_4, compounds of chlorofloro carbons CFCs) into the atmosphere (IPCC, 2007). Therefore, temperature rise is very likely during the 21st century, with may increase to about 1-3^{o}C by 2050 depending on the GHG emissions' scenario. This would led to various impact due to climate change including unprecedented rainfall, melting of arctic and Antarctic ice sheet, sea level rise, more intense storm, etc. (Oyebande, 2012).

Hence, renewable energy plays a vital role in the abatement of the future carbon emissions, thus aiming at reducing overall greenhouse gases. However, renewable energy is dependence on climate conditions, therefore, also susceptible to climate change.

In addition, climate change would have some negative impacts on energy systems although very few positive impacts would be noticeable. Outlined is the summary of such impacts:

I. Increase in temperature are almost certain to reduce demand of energy supply for heating purposes, but increases cooling demand in buildings, for industrial processes and agriculture. Although inter-annual variations will remain constant and cold period or seasons will not disappear.

II. Flooding and drought will continue, impacting the infrastructure (such as reservoir) and the hydro power plant generation and efficiency.

III. Sea rise will be inevitable, this will impact infrastructures along the coastal areas, including tidal generators.

IV. Impact on generation cycle efficiency and cooling water operations of fossil fuel; nuclear and biomass fired power plants will be at risk of climate change.

V. The generation potential of renewable energy will also be affected. This may include:

   a. Hydropower are likely to gain or suffer or both at different times from changes in seasonal rainfall;
   b. Solar generation capability will be affected considerable;
   c. Wind generation may positively or negatively be impacted due to adjustment to local wind;
   d. Biomass or biofuel may be affected due to differences in changes to cultivation regime or period;

VI. Energy transportation infrastructure (for power, oil, and gas) may be affected due to heavy storms, icing, landslides, and erosion due to change in water basin.

Table 2.2.1 summarizes the potential and relevant impacts of climate on the energy systems.

Table 1.2.1. Energy sector vulnerable to climate change. Source (Ebinger & Vergara, 2014).

	Relevant climate impacts			
Item	**General**	**Specific**	**Additional**	**Impact on the energy sector**
Climate change impact on resource endowment				
Hydropower	Runoff	Seasonal flows high & low flows, Extreme events	Erosion siltation	Reduced firm energy Increased variability Increased uncertainty

Wind power	field characteristics	Changes in density, wind speed, increased wind variability	Changes in vegetation (might change roughness and available wind)	Increased uncertainty
Biofuel	Crop response to climate change	Crop yield Agro-ecological zones shift	Pests Water demand Drought, frost, fires, storms	Increased uncertainty Increased frequency of extreme events
Solar power	Atmospheric transmissivity	Water content Cloudiness Cloud characteristics		Positive and negative impacts
Wave and tidal energy	Ocean climate	Wind field characteristics No effect on tides	Strong non linearity between wind speed and wave power	Increased uncertainty Increased frequency of extreme events
Climate change impact on energy supply				
Hydropower	Water availability and seasonality	Water resource variability, Increased uncertainty of expected energy output	Impact on the grid Might Overload transmission capacity Extreme events	Increased uncertainty Revision of system reliability Revision of transmission needs
Wind power	Alteration in wind speed	Increased uncertainty of	Short life span reduces risk associated with	Increased uncertainty on energy output
Biofuels	Reduced transformation efficiency	High temperatures reduced thermal generation efficiency	Extreme events	Reduced energy generated Increased uncertainty

Solar power	Reduced solar cell efficiency	Solar cell efficiency reduced by higher temperatures	Extreme events	Reduced energy generated Increased uncertainty
Thermal power plants	Generation cycle efficiency Cooling water availability	Reduced efficiency Increased water needs, e.g. during heat waves	Extreme events	Reduced energy generated Increased uncertainty
Oil and gas	Vulnerable to extreme events	Cyclones, floods, erosion and siltation (coastal areas, on land)	Extreme events	Reduced energy generated Increased uncertainty
Impact on distribution, transmission, and transfer				
Transmission , distribution and transfers	Increased frequency of extreme events Sea level rise	Wind and ice Landslides and flooding Coastal erosion, sea level rise	Erosion and siltation. Weather conditions that prevent transport	Increased vulnerability of existing assets
Impact on design and operation				
Siting infrastructure	Sea level rise Increased extreme events	Flooding from sea level rising, coastal erosion Increased frequency of extreme events	Water availability Permafrost melting Geo-morphodynamic equilibrium	Increased vulnerability to existing assets Increased demand for new good siting locations
Down time and system bottlenecks	Extreme weather events	Impacts on isolated infrastructure Compound impacts on multiple assets in the energy system	Energy system not fully operational when community	Increased vulnerability. Reduced reliability Increased social pressure for better performance

			required it the most	
Energy Trade	Increased vulnerability to extreme events	Cold spells and heat waves	Increased stress on transmission, distribution and transfer infrastructure	Increased uncertainty Increased peak demand on energy system
Impact on Energy demand				
Energy Use	Increased demand for indoor cooling	Reduced growth in demand for heating Increased	Associated efficiency reduction with increased temperature.	Increased demand and peak demand taxing transmission and distribution systems

2.3 Energy planning models and techniques

This section presents a brief comparative overview of existing energy system models, assessing its suitability for analyzing energy planning and policies of emerging countries. This follows a systematic comparative approach to achieve its purpose.

(Rothenberg, 1981) stated that the usefulness of models has the ability to simplify real and complex events into a more comprehendible representation. Furthermore, for a model to be useful, it must sufficiently address specified problems and not attempting to address the problem of the system as a whole. While, (Neshat, 2014) defined energy models as useful mathematical tools based on system approach and suggested that the best model should be determined based on the problem decision makers or energy planners intend to solve.

As energy planning processes are regarded as being complex, however, modelling of complex problems could lead to better understanding of the system under study and better decisions by providing decision makers and planners of energy system more information about possible consequences of their choices. Therefore, energy models are important tools that have the capacity of helping decision makers, planner, and researchers to overcome complex and complicated problems, be it in the field of energy or climate change.

Due to its complexity, energy system model varies in terms of data requirements, technology specification, and high technical & computing skills. Also, some models are technically ambiguous and tedious, requiring huge data base; conversely, most of the time the skilled and technical man power are not readily available in emerging nations. As a result, most of the energy models were developed in the industrialized countries to address a particular problem which has nothing to do with the real problems faced by the emerging nations. Holden onto this diversity and complexities in terms of its purpose, data demand, compatibility features, it is therefore important to develop models with reasonable and fair adaptability keeping in mind emerging countries.

2.3.1 Empirical review of SD modeling approach

Rapid changes in human activities and behavior, including accelerating economic, technology, and environmental issues have challenged researchers and policy makers to learn and adapt at fast rates to the changing trend. This had had a great impact in the recent past and in today's society, thus, increasing the complexity of the social system. Hence, predicting system actions, policies implementation to tackle social issues and challenges arising from the complex system often fails, exacerbate problems or even create new ones (Sterman, 2000). One of the beneficial tool for effective decision making and solving the anticipated side effects of the past actions, with the ability to learn in a world of growing dynamic complexity, is the application of System Dynamics (SD) methodology, tools, and approach to solving problems (Thanacha & Magzari, 2012)SD, as a tool, as well as a method for modeling and simulating complex, nonlinear and multi-loop feedback system. It utilize the concept of system thinking to improve our understanding of the performances of our social systems related to its internal structure and operating policies.

SD as tool and methodology is applied in various field, this include but not limited to; the power sector planning (Moret et al., 2015; Salman et al.,2016), community planning (urban), business cycle, *i.e.*, cement industry (Ansari & Seifi, 2013), transportation policy and traffic congestion (Armah et al., 2010), issues related with global warming, uncertainties and hydrocarbon modelling (Koul et al., 2016), dynamics in electricity generation capacities (Qudrat-ullah, 2013), renewable energy and CO_2 emissions (Robalino-lópez et al., 2014; Kerem & Hekimo, 2013).

(Herbst et al., 2002) & (Neshat et al., 2014) summarized approaches of characterizing energy models as model type, purpose, and modelling paradigm. He further differentiated between descriptive and normative models. Also, this same author made a comparative review on methodologies in developing energy models. (Sterman, 2002) realized that no model is perfect for all kind of method. They all have their weaknesses and shortcomings.

2.4 Overview of SD modelling approaches

This section presents a brief introduction to SD modelling processes, tools, SD structures, and behavior resulting from feedback loops, including the stock and flow diagrams. Thus, it suggests qualitative aspect of SD.

2.4.1 SD modelling processes

Models are useful as a proactive measure when a problem arises in a system, this indicates a point of action to be taken guiding decision making. However, making the wrong decision could exacerbate the problem, thereby causing more havoc to the system. Thus, this causes a total collapse of the system.

System dynamics (SD) serves as a better method that enhance learning in complex system, thereby conceptualizes and guides decision making by identifying leverage points, understand sources of political resistance and design more efficient policy. Thus, SD is a tool used to avoid the pitfall of making wrong decisions.

This section emphasizes successful the approach to learning about complex dynamic systems, how dynamic models are design using SD tools to elicit mental models.

SD model building is an art process which gives understanding on what to include or ignore so that only the essential features necessarily fulfills the model's purpose (Sterman, 2000; Martinez, 2001). Martinez and Forrester further explained SD building processes as: i) problem identification; ii) system conceptualization; iii) model formulation; iv) model testing and evaluation; v) model use, implementation and dissemination; and vi) design of learning strategy. How this processes are linked is represented in Fig 2.4.1.

i. **Problem identification,** also refers to as boundary selection. Boundary selection involves problems the model is addressed to solve, its variables, concept under consideration, and time horizon, *i.e.*, how far in the past or the beginning of the problem. Thus, it structures the behavior of the system in the past and observable future behavior of the system under study. Sterman, described the problem identification as the most important step in modelling because it clarifies the issue(s) to be solved.

ii. **System conceptualization**. This considers variables and the system under consideration (Sterman, 2000). (Martinez, 2001; Forrester & Albin, 1997). It also considers the conceptual framework as that defines the purpose of the model, identifying the model boundary, key variables involved in the model, diagram of the basic mechanism, and the feedback loop of the system. This, thus, follows the step (i) described above.

iii. **Model formulation.** This is the phase that follows after problem actualization and model conceptualization were determined according to a time horizon. (Sterman, 2000). It describes the model formulation as a dynamic hypothesis as it is a transient phase. It still exposes to change and revision as the modelling process proceeds. (Forrester, 1992) described model formulation as the process of translating system properties (description), step (i) and (ii) above, into levels and rate equations of the SD model and more explicit. The goal here is to be able to identify the endogenous explanations (what influences the system from within). In contrast to this, exogenous variables (what influences the system from outside) are those of assumed variables whose interaction is not within the system in addressing model boundary and the problem articulation. In SD modelling, the numbers of endogenous variables should outshine the exogenous variables.

iv. **Model testing and evaluation.** Model test and evaluation begins when the first equation of the model is written (Sterman, 2000). Testing and evaluating model equations require an assessment and a comparative reference mode of the system. This involves comparison of the problem behavior with the purpose of the model and behavior of the model when subjected to extreme conditions and a sensitivity analysis, given ambiguity in parameters, model boundary, initial, and exaggerated conditions. These are critical tools to discover flaws and errors in the model, giving room for further improvement. Thus, every variable must correspond to a meaningful result in the real world with consistency in dimensions of model equations.

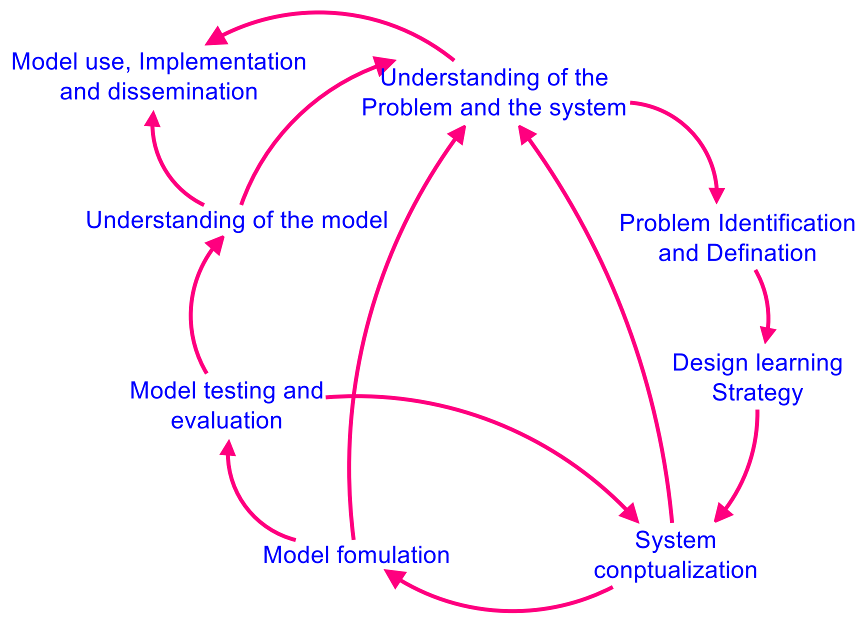


Figure 2.4.1. Overview of SD Modelling Approach. Adapted from (Martinez, 2001).

v. **Model use, implementation, and dissemination**. Model use includes policy design and evaluation (Sterman, 2000). This is seen as the final process to modelling and after which model behavior and sensitivity to perturbation can be ascertained (Forrester & Albin, 1997). Once there is trust in the behavior and process of the model, evaluation of policies and implementation can be designed. This refers to as policy design involving creation of new strategies, system structure, laws, and rules.

Strength of a policy taking into consideration policy sensitivities to ambiguities in model parameters, behavior, and structures must be assessed. This should be carried out under wide range of alternative scenarios and interactions of different policies so as to create synergy and policy reinforcement.

2.4.2 SD modelling tools

In SD, diagrams are used to understand and capture feedbacks and dynamics of nonlinear structure. These diagrams are referred to as tools (Sterman, 2000); they include the causal loop diagrams and stock and flow diagrams.

i. Causal Loop Diagrams (CLDs)

CLDs are cause and effect relationships and form a feedback (interactive) loop. SD models are made up of many feedback loops linked together in a closed system representation. This gives the details about the complexity of such system (Jorgen, 1980). These structures or diagrams presented are called causal loop diagrams. CLD enables better understanding and grip of the general structure of the systems components and interaction among existing components variables. They are suitable for capturing mental models which make them an effective tool at the start of a modelling activity (Sterman, 2000; Forrester & Albin, 1997).

CLDs are guided by some simple rules. A causal loop diagram consists of variables connected by arrows pointing from the independent variable to the dependent variable. At the head of the arrows, polarities are assigned depending on the effect of one variable on the other.

Types of feedback loops

All dynamics arise from the interactions of feedback loops. Positive loops reinforce what is happening in the system, leading to exponential growth. Also, it tends to amplifies while the other type of loop called a negative feedback, counteracts or opposes the trend, thus moving the system towards an equilibrium point or goal (Sterman, 2000; Jorgen, 1980).

(Thanacha & Magzari, 2012) suggested that feedback loops regulate the value of the pointed element or variable by either increasing or decreasing the quantity of interest. The impact of the increase or decrease caused by feedback leads to the structure and behavior of the system.

As earlier mentioned, a causal loop is a cause and effect relationship. Explaining a feedback loop with this notation simple means that a positive feedback loop indicates that if the cause increases, then the pointing arrow head directed variable also increases. Additionally, if the cause decreases, the effect likewise decreases below what it would otherwise have been. On the other hand, a negative link (arrow head) implies that if the cause increases, the effect decreases. Likewise, if the cause decreases the effect increases above the precise quantity of the parameter. (Jorgen Randers, 1980) related these effects as that of a basic algebra sign multiplication principles in Eq. (1) through (4).

$$\text{Positive } (+) \cdot \text{Positive } (+) = \text{Positive } (+) \quad (1)$$

$$\text{Negative } (-) \cdot \text{Negative } (-) = \text{Positive } (+) \quad (2)$$

$$\text{Positive } (+) \cdot \text{Negative } (-) = \text{Negative } (-) \quad (3)$$

$$\text{Negative } (-) \cdot \text{Positive } (+) = \text{Negative } (-) \quad (4)$$

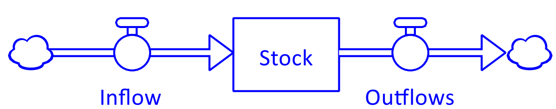
CLDs do not describe or distinguish between stocks and flow, but only show cause and effect relations. They are not comprehensive enough to represent a system. They are always subjected to changes making them provisional and/or transient. Also, they do not account for precise quantitative changes (decrease or an increase) of the elements under concern due to causal relations. They only represent qualitative changes in a system (Rasjidin et al., 2012a).

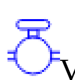
ii. Stock and flow diagrams (SFDs).

This section gives insight on the notion of stock and flow diagrams and their comparative advantages and applications.

It is imperative to know how much of this change has occurred and at what rate it occurred. SFDs give more insight and could account for such precise quantitative changes (Thanacha & Magzari, 2012). The stocks describe the state of the system. They are referred to as level variables and generate the bases of decisions and actions in a system. The stocks according to Sterman, give a system 'inertia, memory, and delays'. While flows are referred to as the rate at which information flow into the stock, they can be increasing or decreasing. There are two types of flows: the inflow and out flow. The diagramming notation to stocks and flows are shown in Fig. 2.4.2, depicting the structures of stock and flows.

- Stocks are represented by rectangles (inferring a holding content)
- Inflows are arrows pointing into the stock (implying addition to the stock)
- Outflows are pipes pointing away from the stock (implying subtraction from the stock)
- Valves control the amount of flow into the stock.
- Clouds represent the sources and sink for inflow and outflows, respectively. Sources and sink are assumed to be dimensionless.




Valve (flow regulator)

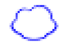
 Source or sink

Figure 2.4.2. Stock and flow structures in SD.

Stocks are usually quantities, while flows are measured in the same units per time period. The concept of SFDs can be likened to that of the principle of a bathtub (Sterman, 2000). Where the bath is the stock and the water flowing in is the inflow and assuming a leakage occurred beneath the bath that is referred to as the outflow. The controller to the inflow and outflow of water are valves.

iii. **Mathematical representation of SFDs**

The net flow into the stock is represented as a rate of change of the stock. Therefore, the Stock is an integral of the net flow added to the initial value of stock refers to as level variable. However, inflow represents the value of the inflow at any time (t) between the initial time, t_o (level) and current time, t. The stock is indicated as an integral equation (5).

$$Stock(t) = \int_{to}^{t}[Inflow(s) - Outflow(s)]ds + Stocks(to) \quad (5)$$

The net flow is therefore the derivative of the total stock with respect to time. This is defined as a differential equation represented in (6).

$$\frac{d(Stock)}{dt} = Inflow(t) - Outflow(t) \quad (6)$$

2.4.3 Structure and behavior of dynamic systems

Combinations of various feedback loops generate a kind of system structure or behavior that describes SD. The major differences between these approaches is their underlining mathematical description of the system (Thanacha & Magzari, 2012). Such structures could include the following:

1. **Exponential growth.** This arises as a result of a self-reinforcing feedback loop. Such structure is as a result of direct consequence of positive feedback. A typical example of an exponential growth can be observed in the case of compound interest earned, where growth continuous as a result accumulation of more money invested, thereby the greater the interest accrues. The general formula for a continues growing compound interest is shown

in Eq. (7). Where, X_o is the initial amount, r is the interest rate, and X (t) is the amount at any time, t.

$$X(t) = X_o e^{rt} \quad (7)$$

An example of such is a bank account being the stock with money at an amount of money at any time, t. The derivative of X(t) with respect to t ($rX_o e^{rt}$) would be the change in the stock (bank account). Drawing the causal loop diagram for this relationship, it would be observed that the loops created are made up of solely positive links. This is shown in the CLD of Fig. 2.4.3a

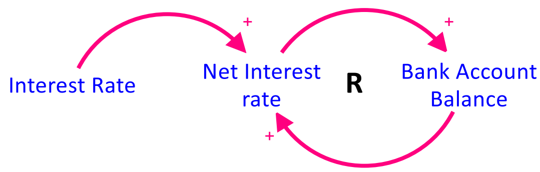


Figure 2.4.3a. CLD for compound interest for a Bank account.

Each element is given its particular role by converting the CLD into a SFD. The net increase rate is therefore, the flow. While, the bank account is the stock and the interest rate is the constant. This is represented as a stock and flow diagram in Fig. 2.4.3b.

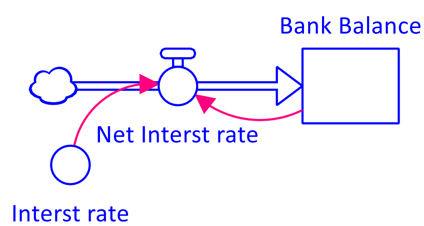


Figure 2.4.3b. Stock and flow diagram of a compound interest.

Fig. 2.4.3c shows the exponential growth of a compound interest of a back account. Therefore, the account balance exhibits an exponential structure as foretold in Fig. 2.4.3a and figure 2.4.3b.

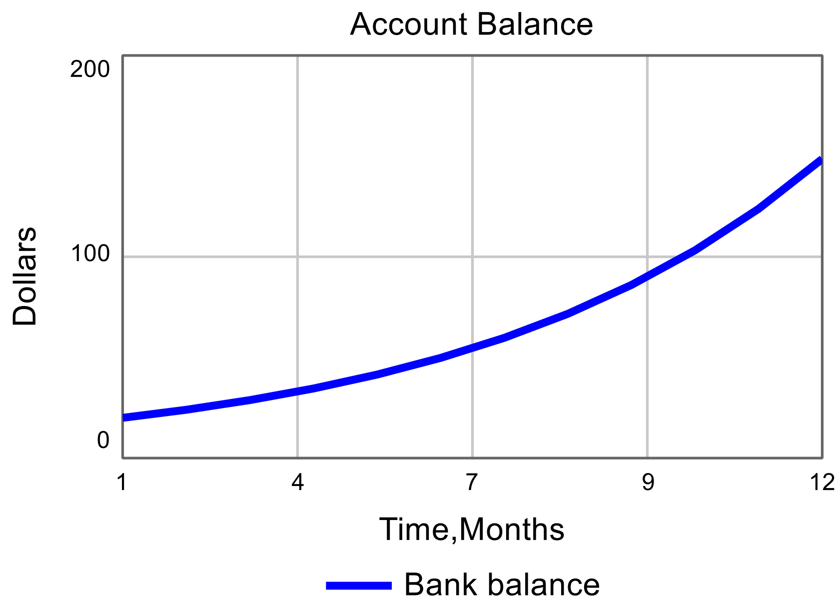


Figure 2.4.3c. Simulation result for a compound interest.

2. **Goal seeking system behavior.** In contrast to exponential growth which is caused as a result of positive feedbacks, goal seeking structure is generated as a result of negative feedback loops. This form of structure seeks to balance, equilibrium creating stability in the system or a desired state by decreasing the stock over time. Thus, they counteract any disturbance that move the system away from its goal by engaging in corrective actions and restores the systems structure. Goal seeking as also aimed to minimize the net flow of a certain stock, as expressed in Equation (8).

$$X(t) = X_o e^{-rt} \quad (8)$$

The negative feedback is intended to control the output and correct it each time it falls out off a desired goal. This is a useful tool to monitor policy changes. For example, if the government is trying to reduce unemployment at the same time abating CO_2 emissions in the country by increasing industries with hopes that the level of unemployment would drop. Such a measure requires a rigorous planning. However, the overall scheme is provided in the CLD illustrated in Fig. 2.4.3d.

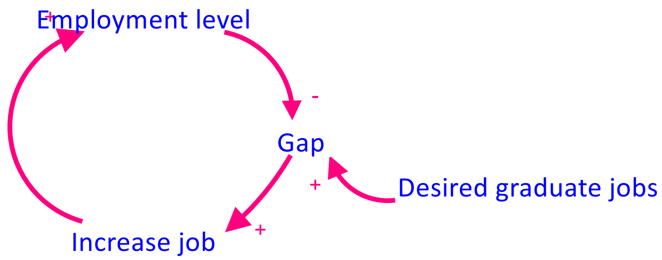


Figure 2.4.3d. CLD for unemployment control

According to the sign on the individual links, the polarity is negative. The gap is the discrepancy between the desired value and the goal. This means each time the stock is fed with a negative feedback, it draws to the required goal (value). This structure is represented in Fig. 2.4.3f

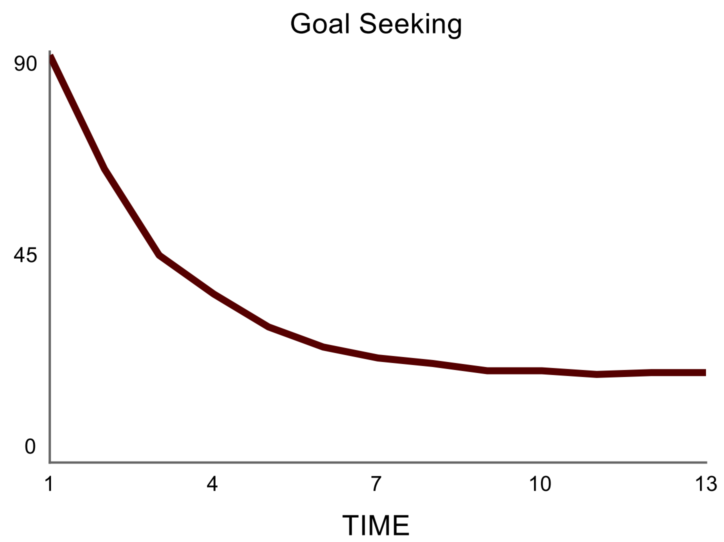


Figure 2.4.3e. Goal seeking structure in SD.

3. **Oscillatory behavior**. Like the goal seeking structure, oscillatory structure is also caused by negative feedback loops. This is a temporal session of the system caused by delay in the system. As a result, delays in a feedback are the real cause of fluctuations in the system. Hence, Oscillatory structure suggests that there is an important negative feedback with significant delays. This implies no real quantity can grow forever, a negative loop must truncate the growth. Such structure is shown in
4. **S-shaped growth.** Here, the state of the system resembles an S shape, as shown in Fig. 2.4.3f. Which indicates a link between a positive and negative loop, suggesting a nonlinear

response (Thanacha & Magzari, 2012; Sterman, 2000). This means that no real quantity can grow or decline forever. This explains the carrying capacity of the system. Sterman defines carrying capacity of any habitat as the number of specific organisms it can support. This is determined by the amount of resources available in the environment needed for the organism's survival.

Furthermore, an S-shaped growth can only be generated if two main conditions are fulfilled:

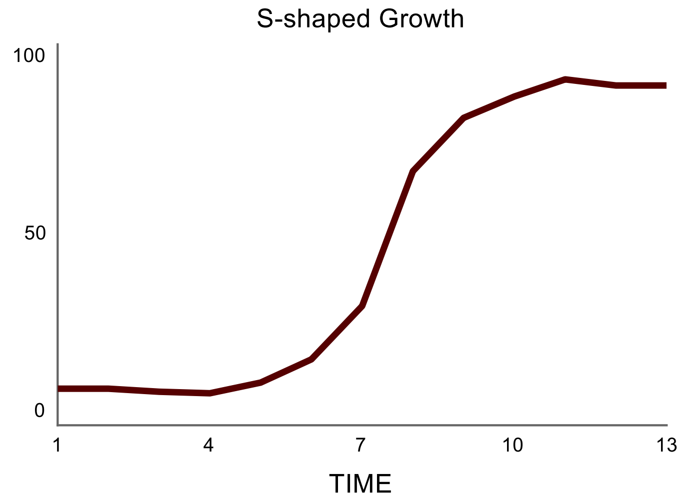


Figure 2.4.3f. S-growth structure in SD.

i) No significant time delays in a negative feedback loop. As it will lead to overshooting and oscillation of growth along the carrying capacity.

ii) Stable carrying capacity. This is to avoid extinction of population by exhausting its resources.

Figure 2.4.3g shows that an overshoot and collapse of the system can occur as a result of depletion on carrying capacity by the population, thus limiting its growth due to the creation of another negative feedback loop (Sterman, 2000).

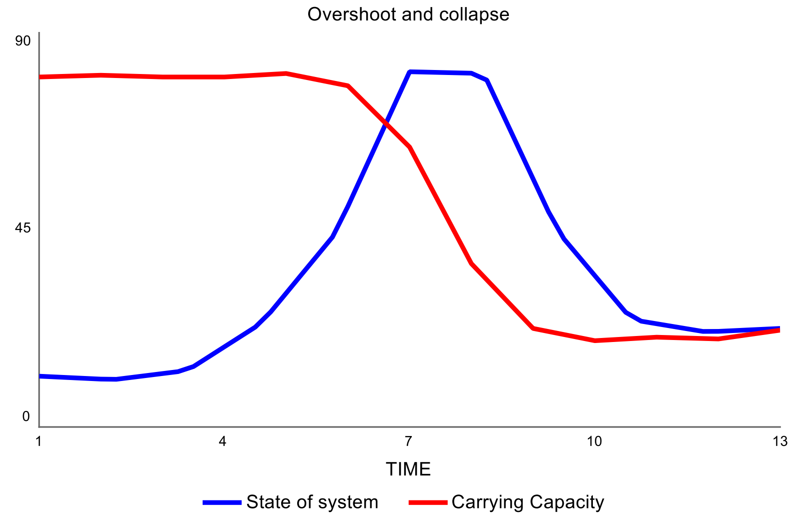


Figure 2.4.3g. Overshoot and collapse

2.5 The Nigerian energy potentials

This section explains energy resources, both RE and non-RE energy potentials, of Nigeria.

Energy resources are regarded as a commodity that drives the economy and wellbeing of any nation, and a prerequisite for socio-economic development of any sovereign state (Bergasse, 2013).

Nigeria is gifted with abundant energy resources, both in RE and non-RE energy resources, which constitutes plausible solutions to addressing the twin challenges of power outages and electricity insufficiencies across the country's power supply sector (NPSI, 2016). Presently, Nigerian major energy consumption sources comes from biomass (81.25 %), natural gas (8.2 %), petroleum products (5.3 %), crude oil (4.8 %), hydropower (0.4 %), and others (less than 1%) (NESP, 2015b).

Electricity generation and production in Nigeria can be dated back over 40 years, with gas fired systems and hydropower generation taking precedence (Ajumogobia & Okeke, 2015). This precedence was based on the fact that the primary energy sources for electricity generation (oil, water, and natural gas) are readily available. While solar power for electricity generation is deployed on a smaller scale for street lighting, lighting, and domestic use in private homes which are not connected to the grid.

Energy sources for electricity generation in Nigeria is attributed mainly to Non-RE and lower amount from RE energies. The non-RE energy resources source include, fossil fuel, varying from gas fired plants, oil fired plants to coal sources, while renewable sources includes hydropower, solar, and wind. Figure 2.5 shows the Nigerian map representing energy resources distribution by regions and states (NPSI, 2016).

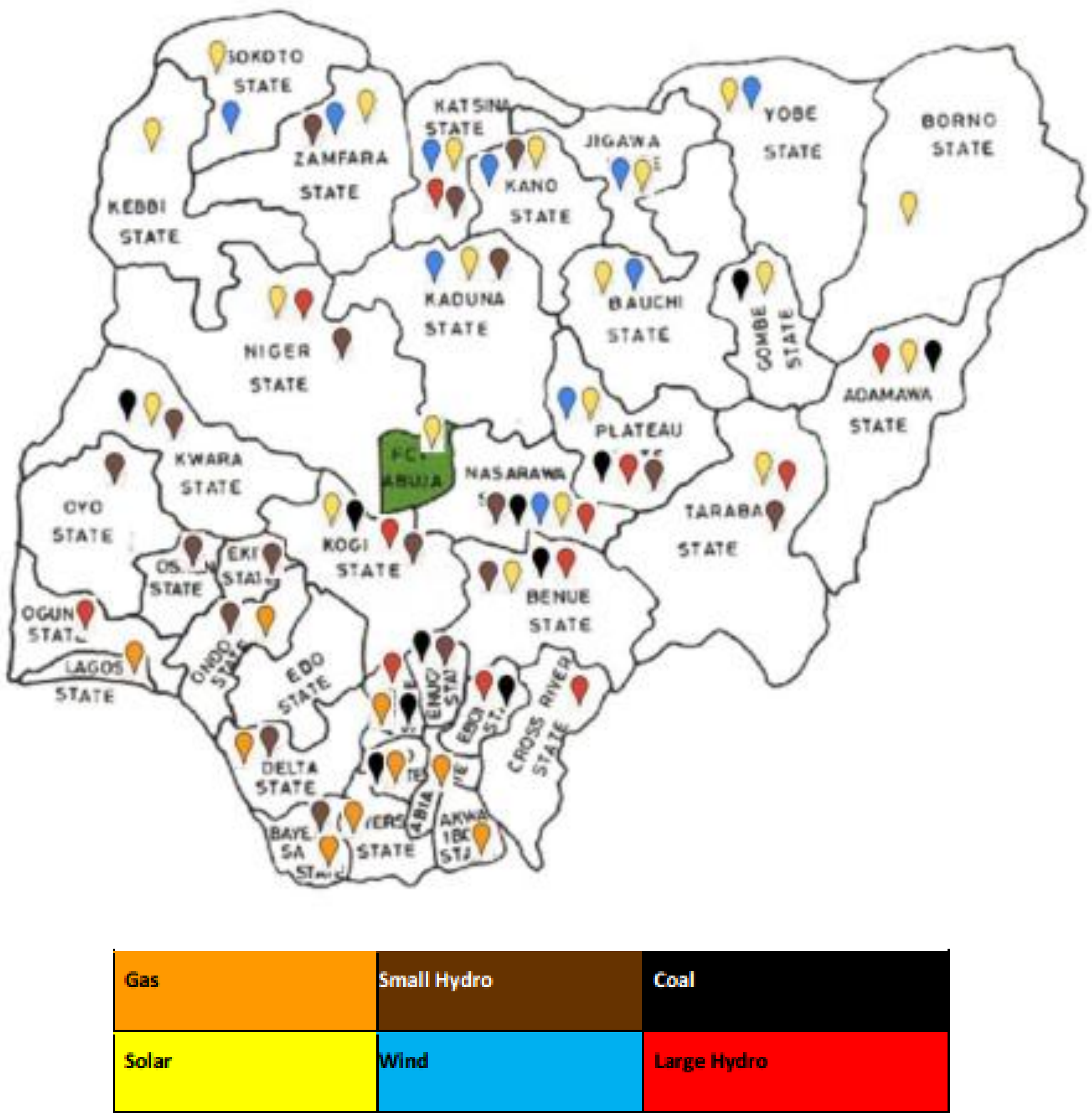


Figure 2.5. Nigeria energy distribution map. (NPSI, 2016).

The large coal reserve (2 billion metric tons) found in Enugu state is yet to be harnessed. In fact, Nigeria has the 10^{th} largest reserve of oil and gas globally, estimated at about 36.2 billion barrel of oil and 1.86 trillion cubic feet of natural gas (Ajumogobia & Okeke, 2015).

2.5.1 Nigeria energy resources and energy mix

According to the Nigerian Power Sector Investment (NPSI) in 2016, growth in the national energy mix would depend upon the completion of the various RE and non-RE electricity projects by the Federal Republic of Nigeria (FRN).

a. Renewable energy in Nigeria

The renewable energy sources are those that when tapped they can replenish within a relatively short time by nature. They include hydropower, solar, wind, and biomass. Renewable energy resources have relatively little negative impact on the environment, while they are inexhaustible at a human scale. Therefore, they are energy sources suitable for a sustainable development.

i. Hydropower generation

The Transmission Company of Nigeria (TCN) and the Energy Commission of Nigeria (ECN) estimated the Nigerian hydropower potential at 14.75 GW, but only 1.93 GW (about 14 %) is in use. These are comprising of large, medium, and small hydro power scheme across the country.

- **Larger and medium hydropower potentials**

Feasibility studies have been carried out across the Nation's Rivers and estuary sites to assess their capacities for large and medium hydropower. Table 2.5.1 shows an itemized technical feasibility capacity in Megawatt and annual capacity in Gigawatt-hour of large and medium hydropower potential in Nigeria. Some of the projects are under construction and being funded (Monks, 2017).

Table 2.5.1. Identified large and medium hydropower potential sites in Nigeria. (NESI, 2016)

S/No	Site	River	Technical feasibility capacity (MW)	Average annual energy (GWh)	Category
1	Mambilla	Donga	3,600	18,702	Large
2	Lokoja	Niger	1,950	8,540	Large
3	Onitsha	Niger	750	3,250	Large
4	Markurdi	Benue	600	4,750	Large
5	Ikom	Cross	400	1,750	Large
6	Yola	Benue	350	1,530	Large
7	Katsina-Ala	Kastina	260	1,140	Large
8	Beli	Taraba	240	1,050	Large

9	Donka	Niger	225	984	Large
10	Karamti	Taraba	200	875	Large
11	Amper	Amper	200	-	Large
12	Afikpo	Cross	180	790	Large
13	Atan	Cross	180	790	Large
14	Garin Dali	Taraba	135	590	Large
15	Gembu	Donga	130	570	Large
16	Manyo yin	Taraba	65	284	Large
17	Kam	Taraba	60	220	Large
18	Suntai	Donga	55	240	Large
19	Su	Taraba	45	200	Medium
20	Sakin Danko	Suntai	45	200	Medium
21	Gudi	Mada	40	180	Medium
22	Kiri	Gongola	40	180	Medium
23	Richa 1	Mosori	35	150	Medium
24	Kombo	Gongola	35	150	Medium
25	Gwaram	Jama'are	30	130	Medium
26	Ifan	Osse	30	130	Medium

- **Small hydropower potential**

Small hydropower potential in Nigeria is easily achieved by converting existing dams into hydropower stations serving a dual benefit of irrigation and electricity generation. To this end, there are already 25 dams in Nigeria capable of generating an estimated amount of 30 MW if converted to hydropower plants (NESI, 2016). Therefore, Fig. 2.5.1a shows the map of location of potential small hydropower sites in Nigeria.

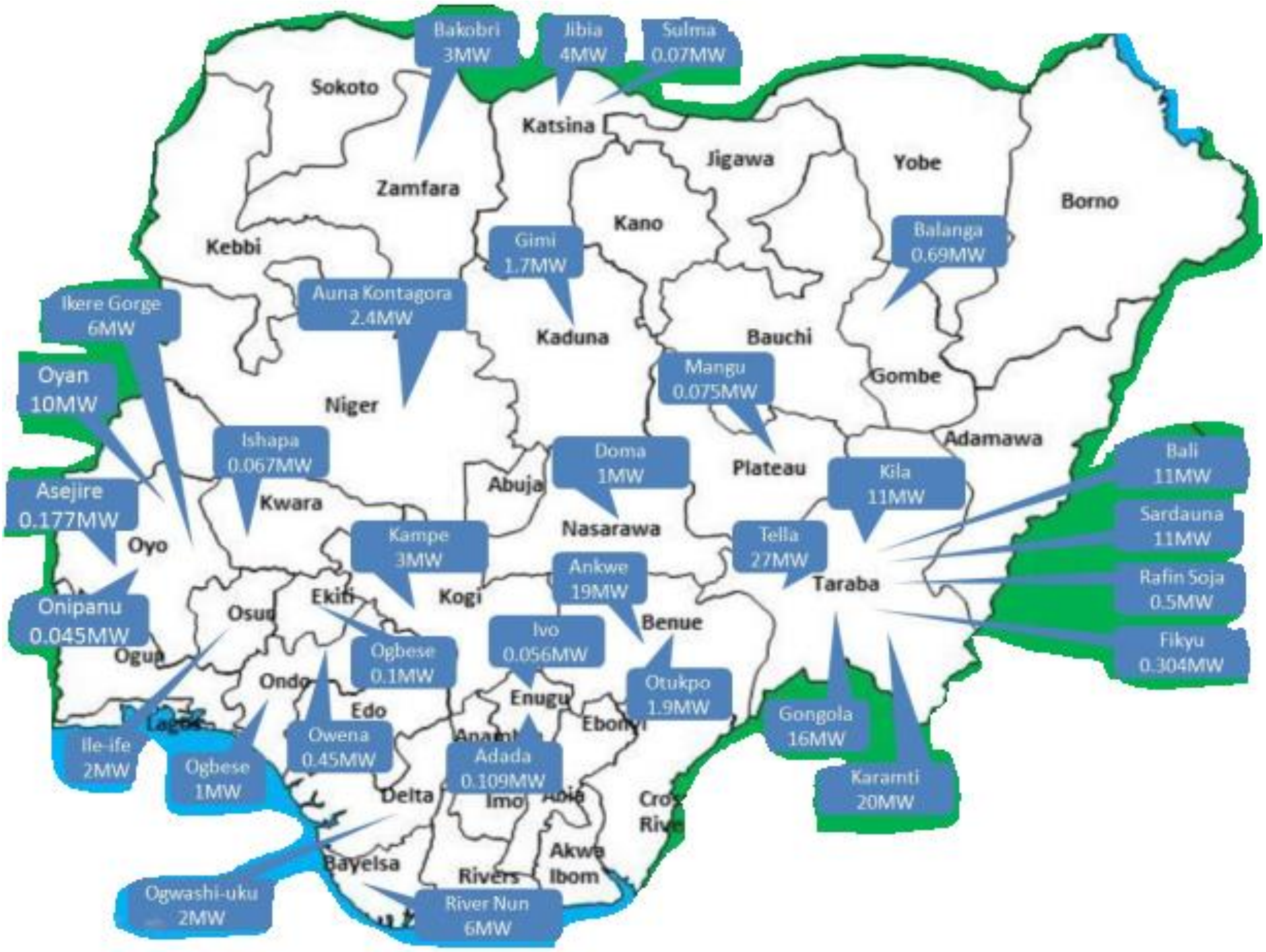


Figure 2.5.1a. Map showing location of small hydropower potentials across Nigeria (NESI, 2016).

ii. Solar energy potential

Solar energy is the type of energy that can be produced from the sun. This energy can be captured by solar panels or solar thermal plants to generate electricity. Hence, Nigeria has a solar potential of 3.5-7.0 kWh/m^2/day (4.2 million MWh/day at 0.1% land area). The Northern Nigeria has some of the highest solar radiation in the world, having solar irradiation which exceeds 2200 kWh/m^2. Solar energy development is environmental friendly, consequently reducing global environmental pressure. They also have a short constructing time compared the conventional power plants that are based on fossil fuel sources.

Figure 2.5.1b shows the distribution of solar irradiation, indicating places with the highest solar gradient in the country. This shows that the North of Nigeria has the highest solar potential.

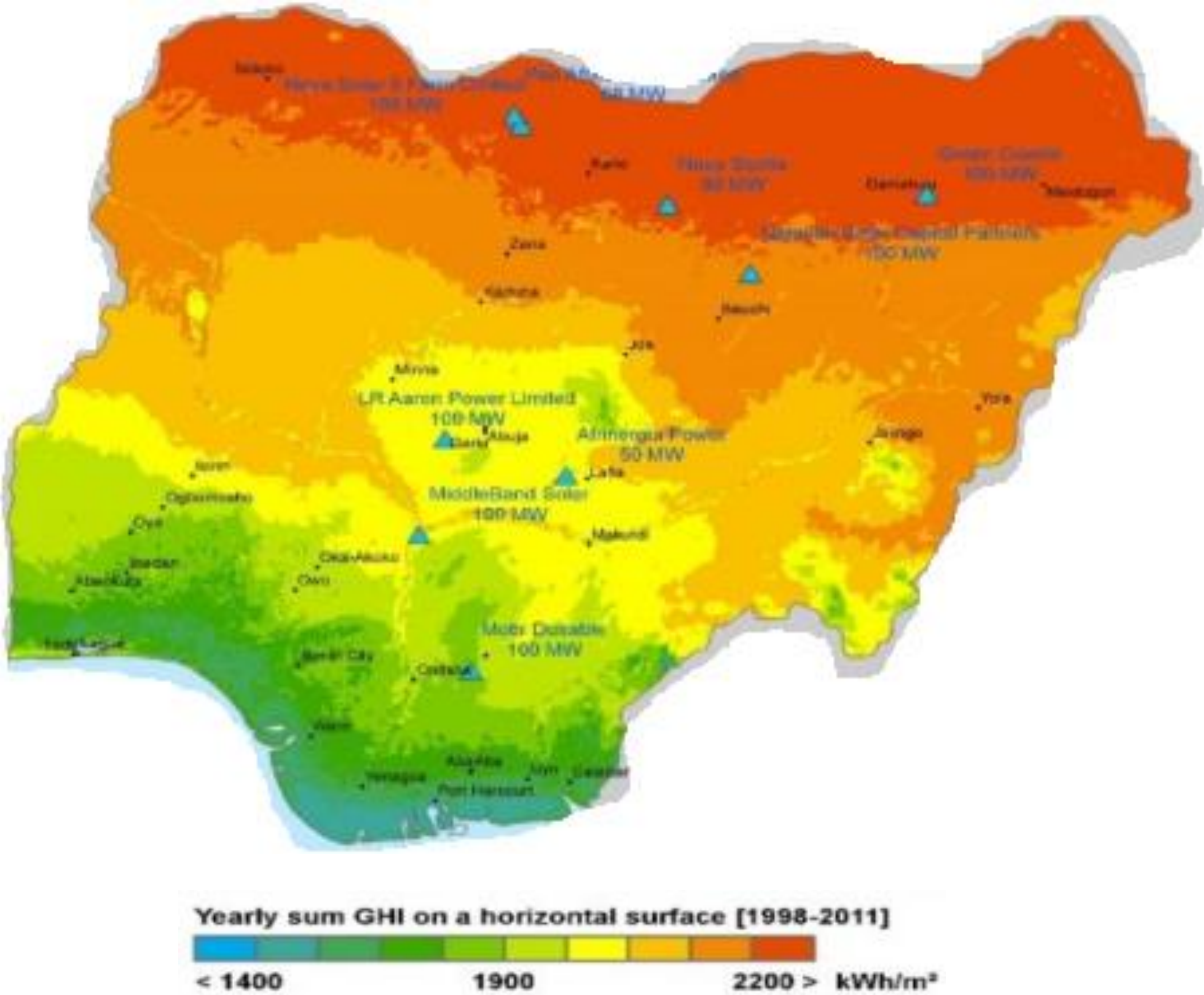


Figure 2.5.1b. Nigeria’s solar global horizontal irradiance. (NESI, 2016).

iii. Wind energy potential

Wind speed can be converted into wind energy in some regions of Nigeria which have very good wind resources. However, the wind speed is considered weak (less than 5 m/s on average) in the southern part, but stronger in the coastal area and hilly regions in the Northern parts of Nigeria. As a result, the wind potential assessment is represented in Fig. 2.5.1c. According this figure (Fig. 2.5.1c), some northern states have the country’s highest potential for wind generation with speeds above 6m/s at 10 meters height (ECN, 2009; NESI, 2016).

Currently, there is a 10 MW wind power plant under construction in Kastina, and negotiations are ongoing for the construction of a 100 MW wind power plant in Plateau state (NESI, 2016).

Figure 2.5.1c. Map of wind potential distribution in Nigeria. (NESI, 2016).

iv. **Biomass energy**

This refers to energy that is developed from organic materials, like scrap lumber, forest debris, crops, manure, and some types of waste residue. Biomass is an indirect form of solar energy because it arises from the process of photosynthesis. Biomass resources found in Nigeria include wood, shrubs, forage grasses, and waste from animals, forestry, agriculture, industry, and municipal areas. The Nigerian biomass resources was estimated at 88 × 102 MJ (Nadabo, 2010).

b. Non-renewable energy in Nigeria

Non-renewable energy are energy sources that are formed over a long period of time and when consumed take a geological life time to be replenished, say millions of years. They are exhaustible in nature. Examples include coal, natural gas, crude oil, etc. Their consumption could be harmful to the environment because they emit GHGs when burnt. They also contribute to global warming.

- **Coal**

Nigeria is endowed with an estimated coal reserve of over 2 Billion metric tons, 12. 8 million tons of sub-bituminous coal that can power a 10 GW power plant for 30 years (NESI, 2016). Most of the coal mine in Nigeria are under concession by the federal government. Table 2.5.1b shows the locations of coal mines with the type of coal and estimated amount of deposits which are suitable for coal power plants.

Table 2.5.1. Potential coal blocks. (Source, Ministry of solid minerals).

S/n	Mine location	State	Type of coal	Proven reserve (Mt)	Bore hole records	Coal outcrop seam thickness (m)	Depth of coal (m)
1	Okpara Mine	Enugu	Sub-bituminous	24	20	Many(1.5M)	180
2	Onyeama Mine	Enugu	Sub-bituminous	22.4	20	Many (1.5M)	140
3	Ihioma	Imo	Lignite	N.A	Nil	Many	20-80
4	Ogboyaga	Kogi	Sub-bituminous	107	31	17(0.8-2.3m)	20-100
5	Ogwashi-saba Obamkpa		Lignite	63	7	4(3.5M)	15-100
6	Ezimo	Enugu	Sub-bituminous	56	4	(1.3m)	80
7	Inyi	Enugu	Sub-bituminous	20	4	(0.9-2.0)m	25-27
8	Lafia/Obi	Nassarawa	Bituminous (Cokable)	21.42	123	(1.3m)	80
9	Obi/Nnewi	Anambra	Lignite	N.A	3	N.A	20-100
10	Afikpo/Okigwe	Ebonyi/ Imo	Sub-bituminous	N.A	Nil	N.A	20-100
11	Amansiodo	Enugu	Bituminous	N.A	3	N.A	563
12	Okaba	Kogi	Sub-bituminous	73	Many	(0.8-2.3m)	20-100
13	Owukpa	Benue	Sub-bituminous	57	Many	(0.8-2.3m)	20-100
14	Maiganga	Gombe	Sub-bituminous	>50	Many	0.1-6.1m	10-60

15	Doho/Molko	Gombe	Lignite/ Sub-bituminous	NA	7	0.1-1.3m	20-30
16	Omelewu (Imane)	Kogi	Sub-bituminous	25	25	0.1-5.2m	4-60
17	Lamza-Chikila	Adamaw a	Sub-bituminous	NA	NA	Nil	NA
18	KurumuPindiga	Gombe	Sub-bituminous	NA	NA	Nil	NA
19	GindiAkwati	Plateau	Sub-bituminous	NA	NA	Nil	NA
20	Janata Koji	Kwara	Sub-bituminous	NA	NA	Nil	NA
21	Enugu Ezike	Enugu	Sub-bituminous	NA	NA	NA	NA
22	Akpanya-Ogboligbo (Igalamela LGA)	Kogi	Sub-bituminous	NA	NA	NA	NA
23	Akunza-Duduguru	Nasaraw a	Sub-bituminous	NA	NA	NA	NA
24	Akpuneje/Onyag ed	Benue	Sub-bituminous	NA	NA	NA	NA
25	Janata Koji	Kwara	Sub-bituminous	N.A	N.A	Nil	N.A
26	Ashokpa-Odolu	Kogi	Sub-bituminous	N.A	N.A	N.A	N.A
27	Ebeje-Irabor	Kogi	Sub-bituminous	N.A	N.A	N.A	N.A
28	Akpacha-Ajadoma	Kogi	Sub-bituminous	N.A	N.A	N.A	N.A
29	Ikpo-Abacha	Kogi	Sub-bituminous	N.A	N.A	N.A	N.

- **Natural Gas**

Nigeria is gifted with a high reserve of natural gas among all other African nations. It is noteworthy to mention that most of the NG resources is situated in the Niger delta part of the country. The estimated proven reserves of natural gas in the country is about 182 trillion cubic feet (TCF) with a mean gauge pressure of about 12 bar and a calorific value of 35mJ/m^3. As such, this makes Nigeria the 25th largest producer of natural gas in the world (ECN, 2007).

2.6 Nigerian Energy policies

This section summarizes few of the Nigerian energy policies (course of action) and strategies in the power sector.

2.6.1 National Electric Power Policy (NEPP) (2001)

The national electric power policy (NEPP) was created in March 2001 (NEP, 2003). It was the first policy report to be made in the Nigerian Power Sector (NPS). It came into being due to recommendations made by the Electrical Power Implementation Committee (EPIC), the body in charge of reforms and strategies in the Nigerian power sector in 1999. Its creation in 2001 was aimed at reforming the power sector. The NEPP is spelt out in three steps to be undertaken: i) first was to privatize the National Electric Power Authority (NEPA), which was state-owned and introduced Integrated Power Producers (IPPs) of electricity; ii) second was to increase competition in the NPS, gradually remove subsidy and sell excess power to the DISCOs; and iii) third was an expectation to complete the liberalization of the electricity market (Maduekwe, 2011). The reform was also in charge of setting up of the Rural Electrification Agency (REA).

2.6.2 National Energy Policy (NEP) (2003), (2006), (2013)

The main goal of the policy enacted in 2003 (NEP, 2003) was to create energy security through an energy mix by diversifying energy supply across the country, this was to be done by increasing the share of renewable energy in the Nigerian energy mix, in order to contribute to sustainable development and environmental conservation in Nigeria. These were to be achieved through a: i) decentralization of energy supply, particularly in the rural areas; ii) development, promotion, and harness of RE resources in Nigeria by increasing the share of RE in the energy mix; and iii) discouragement to use wood as biofuel in the country. The NEP 2003 incorporated some changes and improvement and was first revised in 2006 (NEP, 2006) and later drafted in 2013. The 2013 draft included both environmental and climate change policy. Other areas included were energy planning, financing and policy implementation, man power development and training, and finally bilateral and international corporations (NEP, 2013).

2.6.3 National Power Sector Reform Act (EPSRA), 2005

This was developed as an extension of the NEPP established in 2001 and made provision for new legal and regulatory framework in the power sector. The Electric Power Sector Reform Act (EPSRA) was developed in 2005 to ensure the full liberalization of the NPS and it gave way to the unbundling and privatization of the power sector with the intension of creating competition in the electric market. The main provision of the act includes the: a) creation of a power holding company, PHCN to assume liabilities and facilities of NEPA; ii) unbundling of the PHCN into GENCOs and DISCOS; iii) establishment of the Nigerian Electricity Regulatory Commission (NERC) and the Rural Electrification Agency (REA). The act also provides an investment friendly environment for investors in the energy sector (Ajumogobia and Okeke 2015).

2.6.4 Renewable Policy Guidelines (Electricity REPG), 2006

The REPG enacted in 2006 aimed at increasing electricity generation by the Federal Government of Nigeria (FGN) from RE to at least 5% of the total electricity generated (REPG, 2006) and a minimum of 5 TWh of the total electricity generated in the country. This policy document presents the government plans to promote electricity generation from renewable resources.

Similar policy to REPG is the Renewable Energy Master Plan (REMP), 2005. In 2012, the policy expresses the Nigerian authorities' vision and sets out the road map for increasing the role of RE in achieving sustainable development. It also elaborates the National Renewable Energy and Energy Efficiency guidelines. In addition, the National Renewable Energy and Energy Efficiencies Policy (NREEEP) in 2014 outlines the global thrust of the policies and measures for the promotion of renewable energy and energy efficiency (NREEEP, 2014).

CHAPTER THREE

METHODOLOGY

3.1 System under study

This seeks to study the Nigerian Electric Power System, NEPS, with emphasis on electricity generation, supply, and demand. It also assesses the subsequence GHG emissions from generation plants in a climate change context.

3.1.1 The Nigerian geography, climate, and economy

Nigeria is located in West Africa with a land area of about 941,849 square meter and an estimated population of about 140 million based on 2006 census provisional results, with an average population growth rate of 2.5% (NBS, 2014). Nigeria shares border with the Republic of Benin to the west, Chad and Cameroon to the east, and Republic of Niger in the North. Figure 3.1.1 shows the map of the study area and its political boundaries (NESP, 2015).

Temperatures across the country are relatively high, with wide regional variations. There are mainly two pronounced seasons in Nigeria: the rainy season (April to October) and the dry season usually spanning from November to March. The dry season commences with harmattan wind, a dry chilly spell that lasts till February and is associated with lower temperature and dust brought by winds blowing across the Sahara. The second half of the dry season is always hotter (33^{o}C to 38^{o}C) (from February to March). There is a considerable variation in the annual rainfall of the country (NESP, 2015). The maximum annual rainfall occurs usually in the southeast with an average of about 4000 millimeters. According to (Peel et al., 2007), in its updated climate zones of the world map, Nigeria has five climatic zones, ranging from tropical rainforest climate in the south to dry desert climate in the north.

Figure 3.1.1. The map of Nigeria. Source (NESP, 2015b).

The major drivers of the Nigerian economy are oil and gas industries (chukwueyem et al., 2015). However, there are agitation to diversify the economy into other productive ventures, which include agriculture and the campaign to patronize "*Made in Nigeria*" goods.

3.1.2 The Nigeria Electric Power System (NEPS)

Importance of the electricity sector of a nation cannot be fully underestimated in its developmental processes (UNDP, 2000) due to reasons of weak and dilapidating stage of development regarding electricity generation, transmission, distribution, and infrastructure in the Nigerian power sector. Hence, NEPS has gone through several phases of energy policy reforms.

The Federal Government of Nigeria (FGN) decided in 1972 to merge the Niger Dam Authority (NDA) and the Electric Corporation of Nigeria (ECN). Since then, the former (NDA) was solely responsible for distribution and sales of electricity in Nigeria, while the latter (ECN) was in charge of building and controlling generation stations and maintaining transmission lines. Further, with the merging of NDA and ECN in 1972, a new denomination known as National Electric Power

Authority (NEPA) came to being (Oladipo & Temitayo, 2014). This was due to reasons of achieving better supervision of Nigeria dams and has been solely responsible for all the activities of electricity generation, transmission, and distribution (NESP, 2015). The main aims were to improve the supply and distribution of power across the country, while the act that created NEPA monopolized all its activities by preventing any competition in the field. Thus, private investors were entangled and force to disappear. Also, the Federal Ministry Power (FMP) conducted intensive regulations in the power sector.

The total installed power generation capacity of NEPA's was over 5000 MW, up of 8 production stations, 28 major transmitting stations, and 45 distributing regions. The production stations were a total of three hydropower stations at Kanji, Jebba, and Shiroro with a mixed capacity of 1930 MW. In addition, there are five thermal stations in Afam, Sapele, Egbin, Ughelli, and Ijora with a mixed capacity of 3708 MW (IEWI, 2017; NIB, nb).

NEPA was handicapped by inefficiencies in operation and financial performance due to weak management and bad bureaucratic nature, discouraged innovation, and encouraged corruption in the sector. The increasing population also contributes to insufficiencies in electricity generated in meeting power demand. These challenges led the FGN to acknowledge the National Electric Power Policy (NEPP) and amendment of electricity and NEPA Acts by the FGN in 1998.

NEPP set the road map for privatization of NEPA and finally it's legislating and defunct in 2005. Thus, removal of NEPA sole control and management so as to encourage private sector participation and competition in the sector. This became the Electric Power Sector Reform Act of 2005 (EPSRA)

NEPA was incorporated to form the Power Holding Company of Nigeria (PHCN) plc in 2007. Nigeria privatized the state controlled PHCN with hopes of increasing power generation and improve private investors. PHCN seized to exist in 2013 following a full transition of generation and distribution of the private sector (Emodi, 2016).

The FGN sold all its stake in NEPS, but retained control of the transmission grid (Transmission Company). The FGN is controlled by the National Control Center Oshogbo (NCC) (Emodi, 2016). Also, the FGN sold the generation companies and renamed it GENCOS, while the distribution companies were named DISCOS. This steps were taken at the final stage of unbundling PHCN.

In 2010, the power sector road map was lunched. Its aim was to achieve "*the vision 20 : 2020*" target of 40000 MW. This simply implies that the yearly generation capacity would be grown by 4.3 GW (NREEEP, 2015) and that all potential obstacles to private sector investment would be removed. This aimed at encouraging private sector's participation, but this did not happen.

The success of the reform could be observed in Figure 3.2.1 as the electricity power consumption per capita stood at 178.38 KWh in 2013, compared to 74.13 KWh per capita recorded in 2000, thus representing a significant increase of 140.6 per cent over the period. This development was attributable to a huge demand for electricity requirements by households and firms during the decade (Ogundipe & Apata, 2013), improvement in generation and curtailing losses in transmission and distribution as later shown in Figure 3.1.3b.

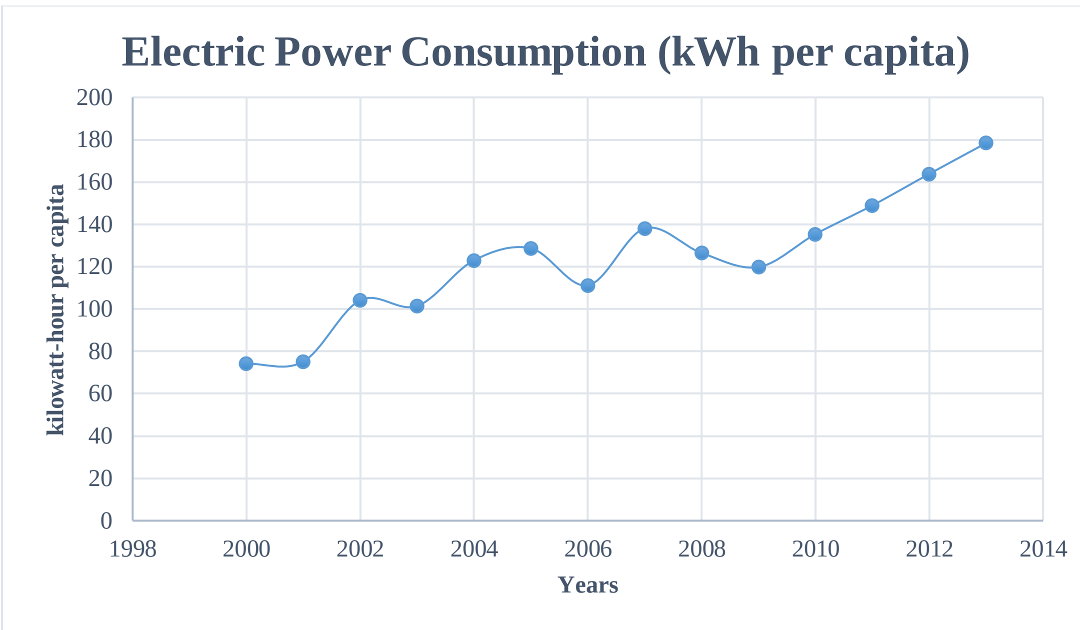


Figure 3.1.2. Electricity consumption per capita (kWh/capita).

3.1.3 Electricity generation, transmission, and distribution

The total installed capacity of the 25 grid-connected generating plants of Nigeria is approximately 12.5 GW (RECP, 2017), although, many plants suffer from recurrent challenges ranging from inadequate maintenance, frequent trips, severe faults to power leakages that made them unavailable for full evacuation to the national grid.

The Nigerian transmission network has a wheeling capacity of about 5.3 GW and comprises of 159 substations and 15,022 km of transmission line (RECP, 2017).

Figure 3.1.3a shows channels for electricity transmission and distribution lines (network) in the country as of 2015. Additionally, the exporting power lines to the neighboring countries, *viz.*, Benin, Niger, and Togo, are shown.

Figure 3.1.3a. Nigerian transmission grid system (Source: Transmission Company Nigeria).

The cost of electricity generation and distribution remains the main constraint to a wide-range availability of electricity throughout that country. This fact seriously impeaches the any economic and social developments at regional and national levels. However, electricity generation data according to Figure 3.1.3b showed an improved electricity generation in recent years from 14.73 TWh in 2000 to about 27.03 TWh in 2011. This represents an increase of 54.3 % (World Bank, 2015). In spite of this, electricity consumption is yet to improve significantly in meeting national demand (represented in Figure 3.1.2).

Figure 3.1.3b displays electricity generation, consumption, transmission, and distribution losses. It follows that electricity transmission and distribution losses were lower in 2000 to 2006, but had improved from 2007 to 2013. This could be attributed to the unbundling of NEPA.

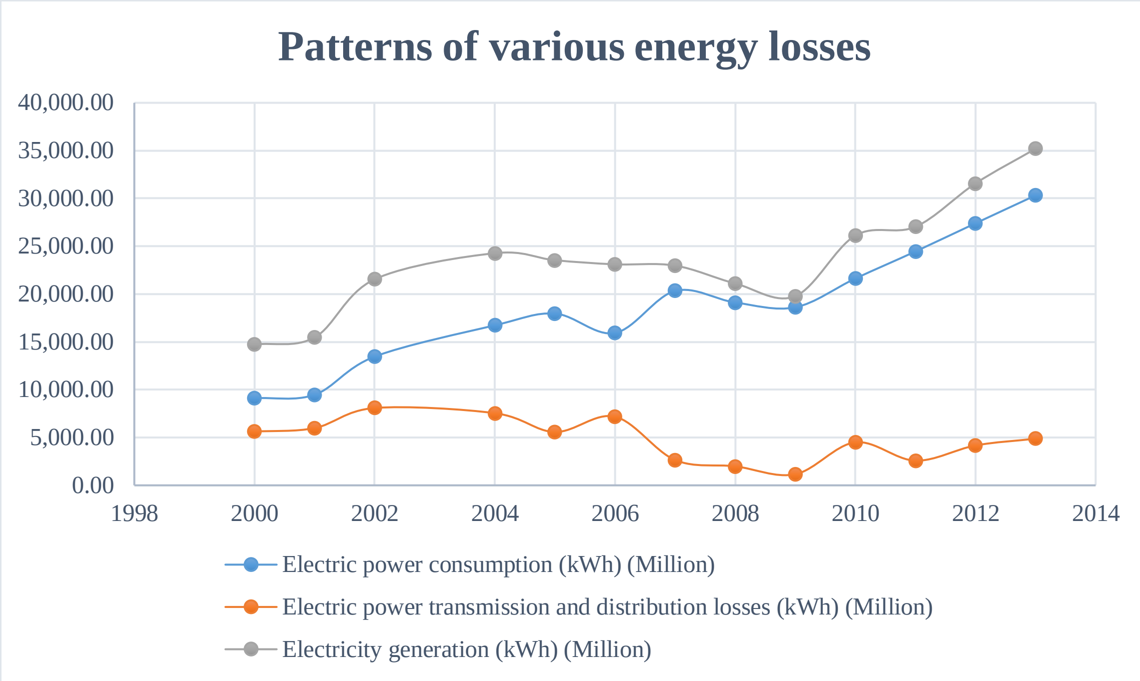


Figure 3.1.3b. Electricity consumption, generation & trans-distr. losses (TWh). Source: TCN and World Bank Indicator Database (2015).

3.1.4 General hypothesis of the system under study

This system under study is the Nigerian Electric Power Sector (NEPS) illustrated in section 3.1.2. The study hypothesized that electrical power security would be attained in NEPS at the horizon of 2024 upon completion of the Mambilla Dam and development of other projects which are presently under construction; this includes both renewable energy (RE) and non-RE projects, thus achieving a more sustainable energy mix. Moreover, the influence of population growth, its impact on energy-demand gap and electricity per capita are all considered. Also, emphasis on electricity generation from RE development would significantly reduce emissions of anthropogenic GHG, abate global warming, and subsequently partake in the fight against climate change.

3.2 Conceptual framework of the study

This section explains the structure and principal context that underline the study.

The framework for this study aimed at assessing the impacts of various future electricity generation projects, considering mainly the completion of the long-proposed Mambilla Multipurpose Hydro-power Dam (MMPH) and the likelihood of its future contribution in bridging the gap between electricity supply and demand An important outcome of the study would serve as a call to action to the government, policy makers, and private investors in the energy sector to invest in the sector in a timely manner to increase electricity generation from renewable energy sources, in a view to reducing emissions.

The Conceptual Framework (CFW) explicitly identified key components in NEPS, including factors of electricity generation, supply and demand, and GHG emissions using a feedback control system based on System Dynamics (SD) principles. Feedback (FB) perspective in SD has the ability to generate shifts in loop dominance and capture the shifting nature of reality (Sterman, 2000). FB is the fundamental method of both capturing and advocating nonlinear models in order to explain the social system behavior, such as the NEPS in CFW.

Figure 3.2 shows the interconnectivity in CFW sectioned into three basic parts: i) the input; ii) the system; and iii) the output. The input section consists of variables that serve as drivers of the system behavior from which it derives its structure. These include different related policies on energy development, investment decisions, labor, existing infrastructure, and regulatory institutions. It is worth mentioning that a similar approach was used by Momodu, (2012).

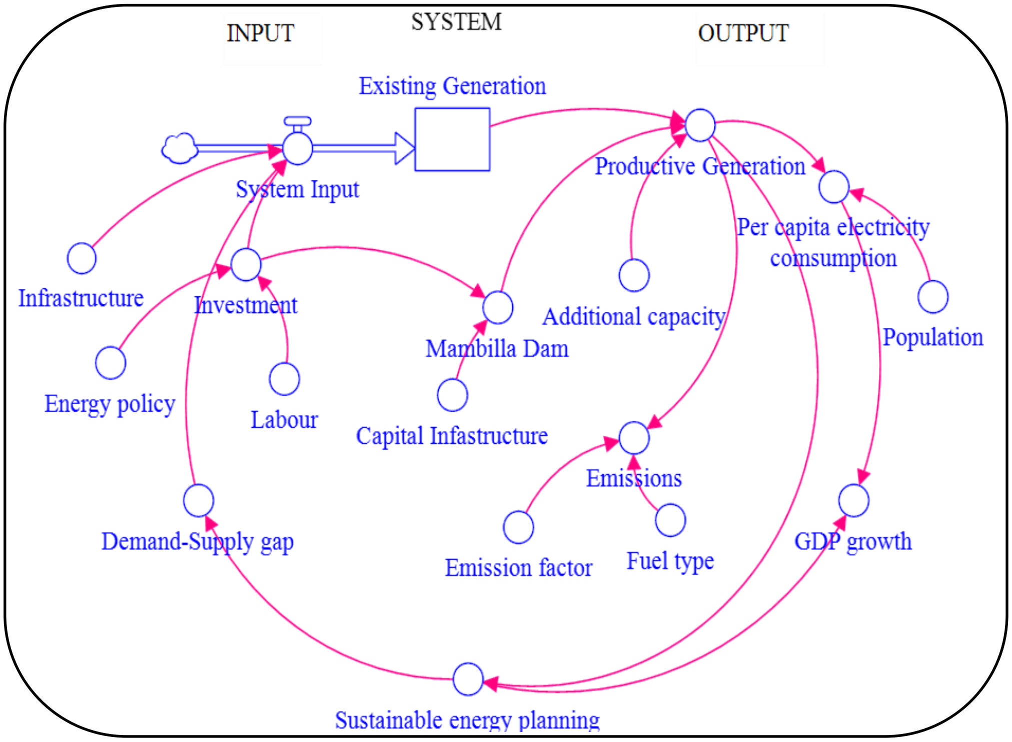


Figure 3.2. The conceptual framework of study.

The system itself, aside from the MMPH, examined other generation technologies in the existing generation mix. These consist mainly of hydro and thermal turbines. Other possible sources of generation captured, as additional capacities, such as coal and renewable sources (solar, wind, and small and/or mini-hydropower plants) were included in the system analysis. The aim was to establish their likely emissions of greenhouse gas (environmental aspect/climate change) and their electricity generated that would be added to NEPS, should they be considered in the future energy mix of the country. The output from the system is the productive electricity generated, while the feedback could be measured from changes in per capita electricity (PCE) consumption and emissions of greenhouse gases (GHG). These variables (PCE and emissions of GHG) were also chosen to serve as performance indicators. PCE indicator is a function of population and the Gross Domestic Product growth GDP. This indicator is determined by the PCE, the effective electricity generated, and the sustainable energy planning, while the drivers of emissions are mainly emission factors and the generating fuel types.

3.3 Data acquisition

The qualitative model of NEPS formed in the CFW of the study inspired the means and data variables that were collected.

The study relied on secondary data that provided the necessary information for the model. The secondary data were sourced from various developed electricity models, regulatory approaches, and regional electricity commissions (Momodu et al, 2017). This includes: 1) the Nigerian Electricity Regulatory Commission (NERC), 2) the Transmission Company of Nigeria (TCN), and 3) the National Control Centre (NCC) Oshogbo. Data collected from these sources include the: a) daily peak electricity generation; b) daily lowest electricity generation; c) daily electricity recorded; d) national peak demand forecast for the period of 2005 to 2015; e) installed capacity as of 2010; and f) available capacity as of 2010. Some of the data were subjected to further analysis to enable estimation of some other variables used in the model, such as capacity factor and the like. 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 indicators, and published articles.

3.4 Modeling Nigerian power sector

This section describes the modelling requirements and processes of the framework and the study's boundary conditions.

3.4.1 Model requirements

With the research objectives in mind, an SD model to study NEPS generation, supply and demand, and GHG emissions was developed using the software program known as STELLA pro (isee systems, 2017). This is perfectly done in accordance with the research questions as stated in chapter one. The model requirements are therefore coined from not only problems to be addressed for decades to come, but also from the corresponding established research objectives. These are:

1) Concrete understanding of the systems behavior. This is the ability to fully understand the working principle underlining operations in the NEPS.
2) Identifying the stock variables (stocks), flows, and constants in the system under study.
3) The Mathematical equations that inter-link variables and SD built-in functions.

4) The qualitative phase of the model construction. This is the conceptual model consisting of causal diagram and stock and flow diagram.
5) Finally, the stock and flow diagram that is translated to a simulation program using SD software for developing the dynamic model. Hence, this forms the quantitative phase of model.

From points 4) & 5) above, the model requirement is in two phases, i.e., i) the qualitative phase and ii) quantitative phase (Rasjidin, et al. 2012). The qualitative forms the model structure through the causal loop diagram (CLD), while the simulation process is required at the quantitative phase.

In STELLA, the stocks simulate the systems dynamic behavior using integration techniques. The Euler integration method was adapted in STELLA modelling platform. This is capable of depicting continuous changes taking place within the system (Thanacha & Magzari, 2012).

3.5 Mathematical framework and model overview

This section gives information about the mathematical framework behind the model's CLD that translates into the stock and flow diagram.

3.5.1 Causal loop diagram (CLD)

The SD model of NEPS used are categorized as electricity generation, electricity supply-demand, population, economy, processes of emissions, and additional supply generation sections. As one of the main and first step in building a successful SD model, the CLD has to be developed to analyze relationship of key variables with respect to the aforementioned sectors in an "*if or condition scenario*," as shown in Figure 3.5.1. This is within the boundary condition of the study.

In Figure 3.5.1, interactions among 25 variables are interconnected and represented by arrows with positive and negative signs. The arrow illustrates directions, while the sign at the end of the arrow show its polarity (Sterman, 2000). A positive polarity indicates that both variables change in the same direction, while a negative polarity shows that both variables are in the opposite direction.

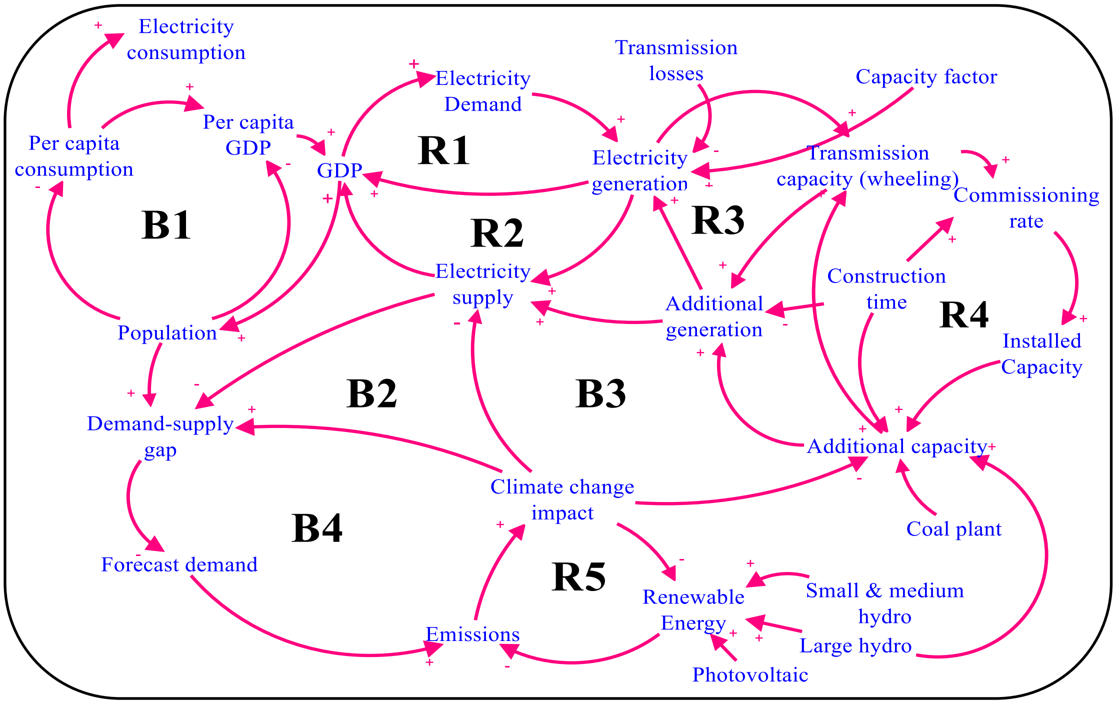


Figure 3.5.1. Causal loop diagram for the electricity sector.

That is, an increase in a variable leads to a decrease in the protruding variable (negative polarity) and vice versa. Also, an increase in a variable will have an increasing effect on the linking variable (positive polarity) and vice versa. Thus, each causal link is assigned a polarity that indicates how the dependent variable changes when the independent variable varies.

A loop is created when two or more variables with similar arrow directions whether it is a clockwise loop (CWL) or an anti-clockwise loop (ACWL) are interconnected. An example of CWL is loop B1, where all variables in B1 forms a clockwise circle. An example of ACWL is represented in loop B3. As a whole, the causal loop diagram has six CWL, namely B1, R1, R2, R3, R4, and R5. It also has three ACWL, namely B2, B3, and B4.

These important loops are highlighted by a loop identifier, which shows whether the loop is a positive or negative feedback. Positive feedback loops are also called reinforcing loops and are denoted by R (no negative sign or even number of negative signs), while negative feedback loops are also called balancing loops and are denoted by B. The CLD consists of five reinforcing loops, namely R1, R2, R3, R4, and R5, while it has four balancing loops, namely B1, B2, B3, and B4.

Table 3.5.1a shows all the variables and polarity in the reinforcing loops.

Table 3.5.1a. Variables and polarity in the reinforcing loops

Loop name	Variables in the loop	polarity
R1	Electricity generation	+
	GDP	+
	Electricity demand	+
R2	Electricity supply	+
	GDP	+
	Electricity Demand	+
	Electricity generation	+
R3	Additional capacity	+
	Electricity generation	+
	Transmission capacity	+
R4	Transmission capacity	+
	Commissioning rate	+
	Additional capacity	+
	Installed capacity	+
R5	Renewable energy	-
	Emissions	+
	Climate change impact	-

Likewise, Table 3.5.1b shows all the variables and polarity in the balancing loops.

Table 3.5.1b. Variables and polarity in the balancing loops

Loop name	Variables in the loop	polarity
B1	Per capita electricity consumption	+
	Per capita GDP	+
	GDP	+
	Population	-
B2	Demand-supply gap	-

	Electricity supply	-
	Forecast demand	+
	Emissions	+
	Climate change impacts	-
B3	Additional capacity	+
	Additional generation	+
	Electricity supply	+
	Demand-supply gap	-
	Forecast demand	-
	Climate change impact	-
	Emissions	+
B4	Demand-supply gap	-
	Forecast	+
	Emissions	+
	Climate change impact	+

3.5.2 Stock and flows diagram (SFD)

The CLD presented in Figure 3.5.1 is further developed into a stock and flow diagram (SFD). SFD is built using variables referred to as the levels or accumulators and the flows are rate of change of level variables. The flows represent activities which fill or drain a stock. These are represented by rectangles and flow valves. While constant are values that are used to compute the rate of change of level variables, connectors, as the name stipulated, connect information flow (Rasjidin et al., 2012b) and (Sterman, 2000). Furthermore, delays are introduced in the model to indicate material flow. These were explicitly explained in chapter two.

Knowing the structure and likely behavior of the system under study via the development of the various CLDs, the behavior of the system was interpreted and shown by developing the SFD model by utilizing historical energy and economic data available to us (2005 - 2015). These include the hydropower plant's capacity under construction, generating capacity, population, and Gross Domestic Product (GDP). Each of these aforementioned quantities represent a stock. Other parameters that were used as baseline are the construction time, capacity life time, time to adjust capacity, population growth rate, GDP growth rate, power demand, and transmission losses.

These represent constants in the model. Other variables that contributed to the structure and behavior of the model were estimated from the available baseline information. These include the initiating capacity, construction rate, scrapping rate, population net growth, and GDP growth. They all are representative of a flow in the model. Other variables estimated were the total electricity generated, electricity distributed, per capita electricity consumption, per capita electricity demand, demand gap, electricity demand, electricity losses, and per capita GDP.

In addition, other variables used as baseline information in the emission sector include emission factors from various generating plant by fuel type and their generating capacities of the future additional capacities. The carbon footprints of various quantities were estimated. Also, the additional energy supply and the subsequent total carbon footprint was calculated. The model was therefore grouped into two sectors: i) electricity generation-demand & supply and ii) added capacity & emissions. Description of the various sections is done in section 3.5.1.

3.5.3 The electricity generation-demand & supply model

The electricity model sector of the study is shown in Figure 3.5.3. This sector is composed of four state variables, each depicting a separate stock. These stocks are comprising of generation, population, economy, and supply-demand.

The generation aspect of the model is composed of two sub-stocks depicting state variables. These are mainly the capacity under construction and the generation capacity, while the population and the economy have one state variable each. These are the population and GDP, respectively.

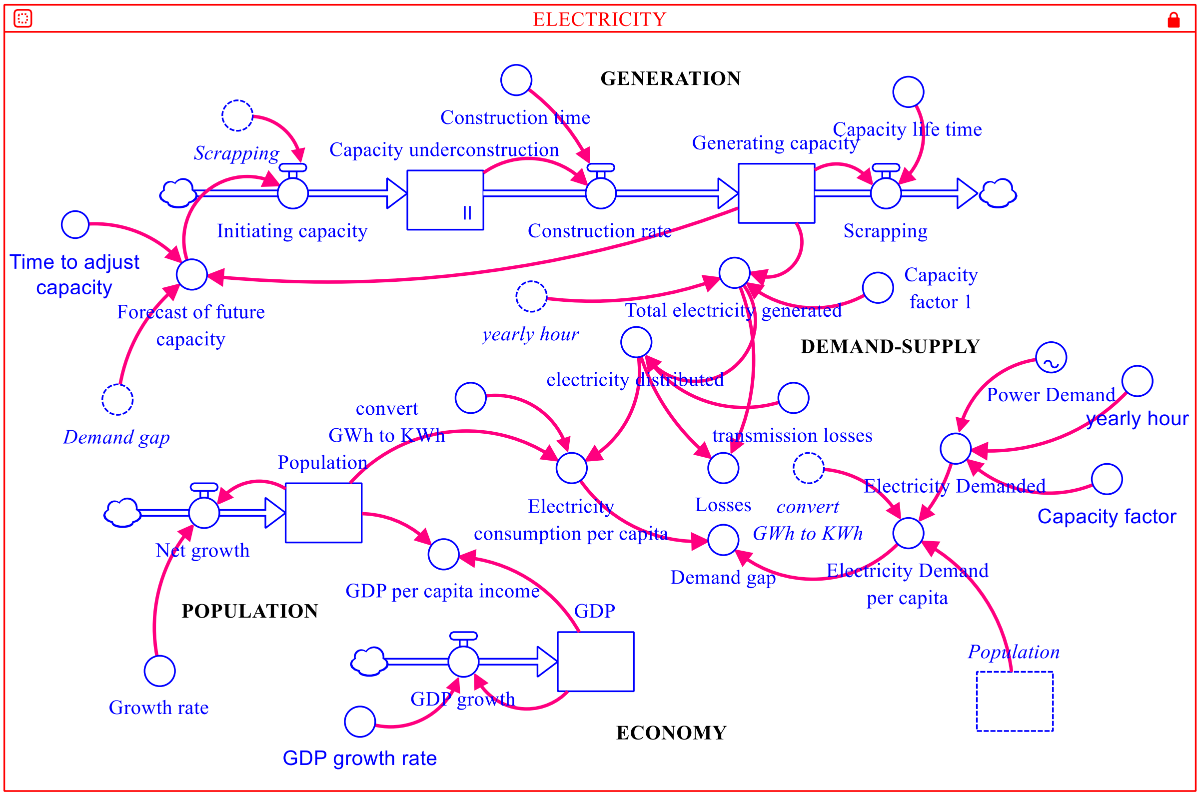


Figure 3.5.3. Nigeria electricity power sector model.

Additionally, this section of the model captured parameters that affect the electricity generation of the NEPS. The variables were chosen to represent the system performance in terms of electricity supply and demand, per capita of electricity demand and income, electricity generation, and transmission losses. As a result, leverage points were identified to be constants, such as capacity factor, transmission losses, time to adjust capacity, etc. The modelling processes of the electricity sector is further explained below.

a) **Generation**: It started with the capacity under construction; it captured the total capacity of electricity generating plants under construction in the Nigerian power sector. It is influenced by the initiating capacity, which stands as a flow. Also, the generating capacity gives the generation at the base year of the study (2010) and subsequent additional generation which was captured with a conditional statement, that is "*IF THEN ELSE*." This statement was adopted because some generation plants were expected to have been completed in a near future time. A material delay was captured in the capacity under construction. Thus, indicating that some delay might be experienced in the construction processes due to some unknown factors. Hence, this fact, not only was it captured as a result of the complexity of the project, but also as a means of predicting the uncertainties of the national economy through the dynamic capabilities of SD in STELLA pro. Other variables and constants, such as forecast of future capacity driven by the demand gap, capacity under construction, and time to adjust capacity in turn drove the initiating capacity earlier mentioned. The construction time influence, the flow construction rate, and the capacity lifetime of plant drive the scrapping rate, thus altogether contributed to make up the generation sub-sector to be economically inclusive and sound.

b) **Supply and Demand**: This sub-sector illustrates the modelling of how the available and future electricity generation could meet present and forecasted demand. From the generating capacity connects the total generated electricity estimated from yearly hours and the capacity factor. Also, the distributed electricity influenced by transmission losses gives the actual electricity distributed by DISCOS. Power demand was captured in the model using the graphical capability of STELLA, *i.e*., the "TIME" built-in function. Electricity consumption per capita and Electricity demand per capita were calculated by dividing the electricity distributed and electricity demanded by population, respectively. Consequently, the demand gap was estimated as a ratio of the electricity demanded per capita and consumption.

c) **Population**: The population net growth is determined as a product of the population at the base year and growth rate. Population determines the per capita of electricity consumed and demanded and the per capita income.

d) **Economy**: This sub-sector modelled the per capita income as a ratio of the GDP and the total population.

Table 3.5.3 shows the equations and units governing the electricity sector as they appear on the rear-panel interface of the Stella software.

Table 3.5.3. Names and equations for electricity sector

No	Names	Equations	Units
	STOCKS		
1	Generating capacity (t)	Generating_capacity (t -dt) + (Construction_rate-Scrapping) · dt	GW
2	Capacity_underconstruction(t)	Capacity_under_construction (t - dt) + (Initiating_capacity - Construction_rate) · dt	GW
3	Population (t)	Population (t - dt) + (Net_growth) · dt	people
4	GDP (t)	GDP (t - dt) + (GDP_growth) ·dt	USD
	OUTFLOWS		
5	Initiating_capacity	(Forecast_of_future_capacity-(Scrapping))	GW/yr.
6	Construction_rate	(Capacity_under_construction)/Constructiontime	GW/yr.
7	Demand_gap	Electricity_Demand_per_capita/Electricity_consumption_per_capita	-
8	Scrapping	Generating_capacity/Capacity_life_time	GW/yr.
9	Losses	Total_electricity_generatedelectricity_distributed	GWh
10	Electricity_consumption_per_capita	((electricity_distributed)·convert_GWh_to_KWh)/Population	kWh/capita
11	Electricity_Demand_per_capita	(Electricity_Demanded/Population)·convert_GWh_to_KWh	kWh/capita
12	Electricity_Demanded	Power_Demand · Capacity_factor · yearly_hour	GWh
13	electricity_distributed	distributed = (Total_electricity_generated)-(Total_electricity_generated) · transmission_losses	GWh
14	Forecast_of_future_capacity	((Generating_capacity))·Demand_gap)/Time_to_adjust_capacity	GW/yr.
	INFLOWS		
15	GDP_growth	GDP_growth_rate · GDP	USD/yr
16	GDP_per_capita_income	GDP/Population	USD/ca
17	Construction_rate	(Capacity_underconstruction)/Construction_time	GW/yr.
18	Net_growth	Population · Growth_rate	Pe/yr.
19	Power_Demand	GRAPH (TIME)	GW
20	Total_electricity_generated	(yearly_hour·Capacity_factor_1·(Generating_capacity)transmission_losses	GWh

3.5.4 Modeling electricity capacity added and GHG emissions

Electricity supply added to the model was done as a result of capacity under construction with a completion date in view. Repairs and upgrading of old natural gas power plants are also in process, but at a slow rate. It is worth mentioning that these two aspects were not considered in the modelling process in this study (Akintayo, 2017). The capacities added included 1 GW of coal power plant expected to be constructed at the horizon of 2022. This was modelled by the "*GRAPH*" built-in capability of STELLA.

The added capacity and corresponding GHG emissions model sector is represented in Figure 3.5.4. This sector depicts the electricity capacity added to the NEPS and equivalent GHG emissions. Also, emissions from existing generation plants, *i.e.*, hydropower and NG fueled plants, were included in the model.

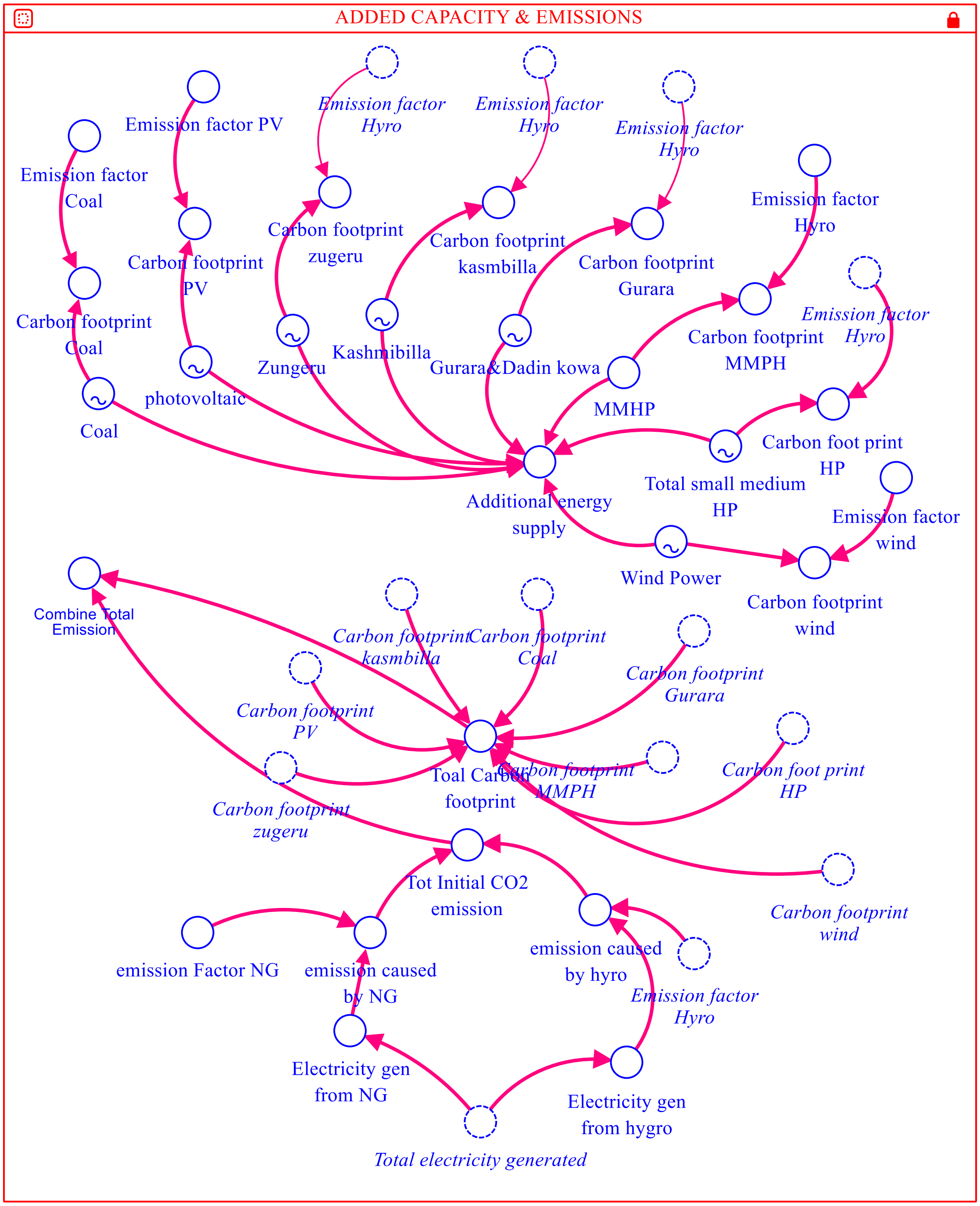


Figure 3.5.4. Electricity capacity added and emissions.

Moreover, renewable energy generation sources, like large hydro power plants including: Zungeru, Kashimbilla, Gurara&dawin kowa, and MMPH are at pilot stage and are expected to be completed at the horizon of 2020, 2020, 2022, 2025, respectively. Photovoltaic (solar plant) capacity of 1.2 MW completion is expected at the horizon of 2023 (Punch, 2016) and (Akintayo, 2017). This renewable source was included in the model. In addition, small and medium hydropower plants of total capacities of 45.25 MW were included. Also, their carbon footprints were estimated, (SEPS, 2007) and (Wen et al., 2016), as a product of the electricity expected to be generated and their emission factors (SEAP), (Benavides et al., 2017). The MMPH capacity was modelled in the study using the "*IF THEN ELSE*" condition. The electricity expected to be added at the horizon of 2025 is 26718 GWh (Monks, 2017), *i.e.*, IF TIME > 2025 THEN 26718 ELSE 0. The usage of the latter conditional statement was supported by (Moumouni et al., 2014).

A power purchasing agreement (PPA) for a thermal solar plant, to be developed, with a capacity of 1.125 GW has been signed (Akintayo, 2017). For simplicity purposes, this additional, but nonetheless capacity, was not included in the model.

Table 3.5.2 presents the equations and units governing the added electricity capacities and the added GHG emissions.

Table 3.5.2. Names and equations for electricity capacities added and emissions.

No	Name	Equation	Units
1	Additional_energy_supply	MMPH+Gurara&Dadin_kowa+Kashmibilla+Zungeru+photovoltaic+Coal	GWh
2	Kashmibilla	GRAPH (TIME)	GWh
3	Gurara&Dadin_kowa	GRAPH (TIME)	GWh
4	photovoltaic	GRAPH (TIME)	GWh
5	Zungeru	GRAPH (TIME)	GWh
6	Coal	GRAPH (TIME)	GWh
7	Carbon_footprint_Coal	Coal · Emission_factor_Coal	unit tonnes CO_2e
8	Carbon_footprint_Gurara	Gurara&Dadin_kowa·Emission_factor_Hyr	unit tonnes CO_2e
9	Carbon_footprint_kasmbilla	Emission_factor_Hyro · Kashmibilla	unit tonnes CO_2e
10	Carbon_footprint_MMPH	MMPH · Emission_factor_Hyro	unit tonnes CO_2e
11	Carbon_footprint_PV	photovoltaic · Emission_factor_PV	unit tonnes CO_2e
12	Carbon_footprint_zugeru	Zungeru · Emission_factor_Hyro	unit tonnes CO_2e
13	Combine_Total_Emission	Toal_Carbon_footprint+Tot_Initial_CO_2_emission	unit tonnes CO_2e
14	Electricity_gen_from_hygro	Total_electricity_generated · 0.75	GWh

15	Electricity_gen_from_NG	Total_electricity_generated · 0.25	GWh
16	emission_caused_by_hyro	Electricity_gen_from_hygro · Emission_factor_Hyro	unit tonnes CO_2e
17	emission_caused_by_NG	Electricity_gen_from_NG · emission_Factor_NG	unit tonnes CO_2e
18	Toal_Carbon_footprint	Carbon_footprint_kasmbilla+Carbon_footprint_Coal+Carbon_footprint_Gurara+Carbon_footprint_PV+Carbon_footprint_zugeru+Carbon_footprint_MMPH + Carbon_footprint_wind	unit tonnes CO_2e
19	Tot_Initial_CO_2_emission	Emission_caused_by_NG+emission_caused_by_hyro	unit tonnes CO_2e
20	MMPH	IF TIME > 2025 THEN 26718 ELSE (0)	GWh
21	Wind_Power	GRAPH (TIME)	GWh
22	Carbon_footprint_wind	Emission_factor_wind · Wind_Power	unit tonnes CO_2e
23	Total_small_medium_HP	GRAPH (TIME)	GWh

3.6 Scenario development and parameters.

Scenarios were considered and developed with a view to the study's objectives, hypothesis, and problem statements. To better understand the dynamics in NEPS and its GHG emissions, an SD simulating model was developed and validated to evaluate six different policy scenarios. A great emphasis was put on the base case scenario or Business as Usual (BAU), as shown in table 3.6. During the simulation process of each scenario and sector, population growth rate and energy demand was kept constant, while varying that of the distribution. This was to observe changes in the system as simulation process proceeds.

Scenario 1. This comprises of population growth rate at 2.68%, time to adjust capacity of 20 years, transmission losses of 7.5%. Additional capacities are switch on. These mean capacities considered in the study were made available for generation. This excluded completion and operation of the Mambilla multipurpose hydropower (MMPH)

Scenario 2. This is similar to that in scenario 1, but the MMPH was switched, thus indicating its availability to generate energy.

Scenario 3. It considered both capacities of added supply and MMPH, population growth rate at 2.68%. It assumes that TAC was made in an earlier year of every 15 years and transmission losses were put at 5%. This, according to Multi Year Tariff Order 2.0 (MYTO 2.0) set target to reduce transmission losses to 5%.

Scenario 4. This considered an adjustment in the population growth rate at about 2% and set the TAC at every 15 years transmission losses of 7.5%. Also, both added supply and MMPH were in operation.

Scenario 5. This includes parameters similar to scenario 4, but has some differences in the TAC 15 years and transmission losses of 5%.

Scenario 6. This scenario was included to check **scenario 4**, *i.e*., the impact of the TAC on the system under study.

Business as Usual (BAU). This was also referred to as base case scenario in the study. It is considered as the natural state of the system before the advent of alteration by any of the scenarios. All the aforementioned scenarios are illustrated in Figure 3.6.

Table 3.6. Summary of the policy scenarios

Scenarios	Population Growth rate	TAC (Years)	Tx	Added Capacity	Mambilla dam
1	2.68%	20	7.5%	on	off
2	2.68%	20	7.5%	off	on
3	2.68%	15	5.0%	on	on
4	2.00%	20	7.5%	on	on
5	2.00%	15	5.0%	on	on
6	2.00%	15	7.5%	on	on
BAU	2.68%	20	7.5%	off	off

These six scenarios aimed to evaluate influence of population growth rate, transmission losses (Tx), time to adjust capacity (TAC), additional supplies and completion, and operation of the long proposed MMPH at the horizon of 2024 in the performances of NPS.

However, these performances would be assessed in: i) the total electricity generation; ii) the total electricity distributed; and iii) both electricity consumption and demand per capita, giving details about the demand gap.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.0 Results analysis and Discussions

This chapter gives the empirical analysis and report findings based on the study's objectives and methodology to arrive at logical conclusions. System Dynamics (SD) modelling approach was used in analyzing both energy and GHG emission data. The main purpose of this, was to evaluate impacts and contributions of generating plants under construction with emphasis on the Mambilla multipurpose hydropower (MMPH) dam and the subsequence carbon footprints, of all the plants, in the Nigerian power sector (NEPS).

4.1 Electricity Demand and Distributed

Figure 4.1 shows electricity demand (blue) versus simulated electricity distributed (red-dashed) in the base case scenario (or business as usual) of the NEPS. It was observed in Figure 4.1, that demand for electricity in the NEPS far exceeds the electricity distributed or supplied from existing generating plants. This certainly explains the frequent power shortages and unplanned load shedding throughout Nigeria. Therefore, this justifies the bases of the study problem statements. As such, 52% of Nigerians have access to electricity and the supply is epileptic in nature.

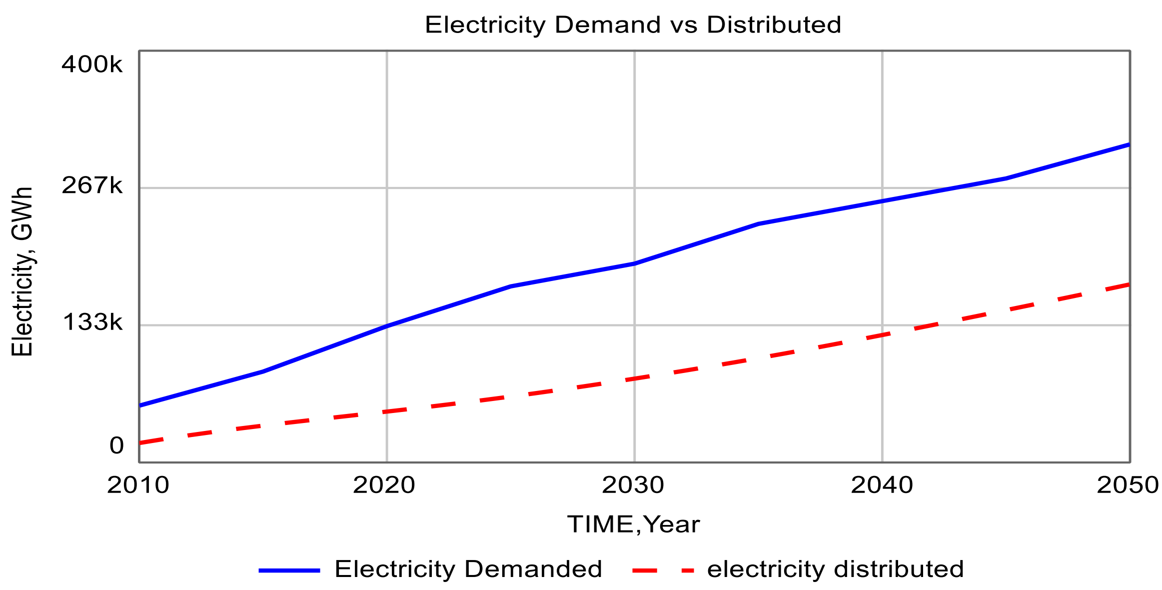


Figure 4.1. Electricity demanded and distributed.

In 2010, the value of electricity generated was 21.92 TWh according to the NESP. This, as seen in the figure, is similar to the value generated from the model (20.4 TWh), thus the similitude is a bases for validating the model.

4.1.1 Electricity Generation

Considering electricity generation for the base case scenario and the other scenarios outlined in Table 3.6, Fig. 4.1.1 shows simulated electricity that would have been generated taking into account the six scenarios. Note that the total electricity generated for scenarios 1 to 6 represent TEGs 1, TEGs 2, TEGs 3, TEGs 4, TEGs 5, and TEG 6, in that order.

It was observed in Figure 4.1.1 that the electricity generated at base case was the same for all scenarios from the beginning of the simulation until 2012 when an increment of added energy in TEG 3, 5, and 6 was about 100 GWh. This was predominantly due to the contribution of other sources of energy, like solar PV, small & medium hydropower, and coal in the added supply. The year 2020 in the simulation also indicated an increase in electricity generated in all the scenarios compared to the base case until 2024 when a main increment occurred due to the completion of the MMPH.

TEGs 1 was composed of a population growth rate of 2.68%, TAC 20 years, Tx of 7.5%, and an added electricity supplies “ON,” but excluded MMPH. TEGs 1 showed an increase in generation of 1.7k GWh over the simulation period as compared to the base case. This was due to the additional supply made to the base scenario.

TEGs 2 and TEGs 4 were run at different population growth rate, 2.68% and 2.0%, in that order, and same TAC and Tx. They closely followed the same pattern and energy values until 2031. In contrast, they started to deviate in energy values from 2033 by 0.87% and 11.69% at the end of simulation (2050). Despite TEGs 2 had MMPH turned “ON,” but no added supply, it recorded higher values of electricity. Conversely, TEG 4, although it had both MMPH and added supply, recorded a lower generation as compared to TEGs 2. It was also observed that energy values in TEGs 4 started depreciation in 2043 below the base case and TEGs 1. This same pattern and sudden variations in energy were not confirmed, but could be a result of variation in population growth rate.

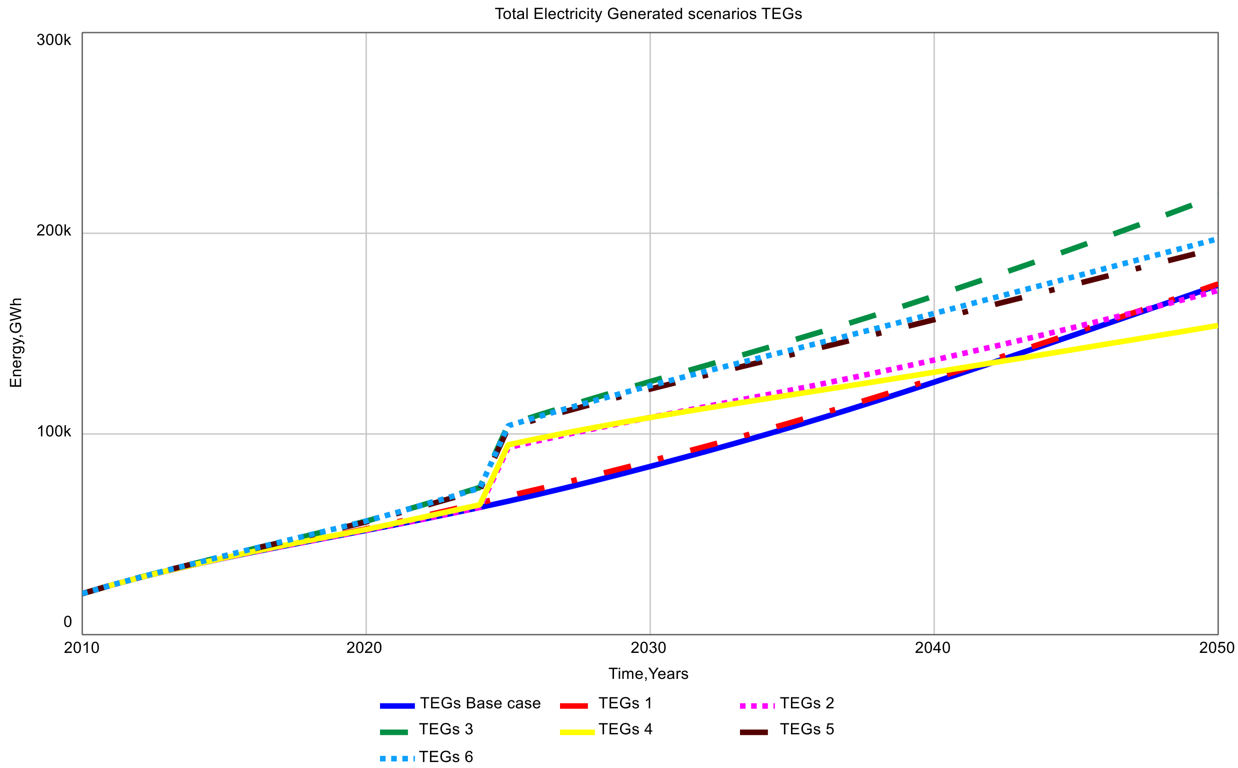


Figure 4.1.1. Total Electricity Generated scenarios.

However, TEGs 3, TEGs 5, and TEGs 6 followed the same increasing trend throughout the simulation period. Nonetheless, they observed a significant variation from 2031 until 2050 as compared to other scenarios with TEGs 3, TEGs 5, and TEGs 6 showing the highest energy generated, respectively. Taking a closer observation at TEGs 3, PGR 2.68%, TAC 15%, and Tx 5% included both added supply and MMPH, the highest electricity generation of about 219 TWh was recorded in 2050.

Consequently, this could be as a result of either or all of: 1) reduced transmission losses, 2) earlier time to adjust capacity (TAC), and 3) a higher population growth rate.

4.1.2 Total Electricity Distributed (TEDs)

From the patterns and trends observed in Figure 4.1.2, the total electricity distributed (TED) is similar to that observed in the TEG of Figure 4.1.1. Also, a lower energy due to a transmission losses of 7.5 % was made in TED base case scenarios, such as TEDs 1, TEDs 2, TEDs 3, TEDs 4, and TEDs 6. In contrast, scenarios TEDs 3 and TEDs 5 were due to 5% transmission losses.

The same trend was observed in TEDs 5 and TED 6 without variations in the energy values. Despite having the same parameters, they differ in Tx, *i.e.*, 5% and 7.5%, respectively.

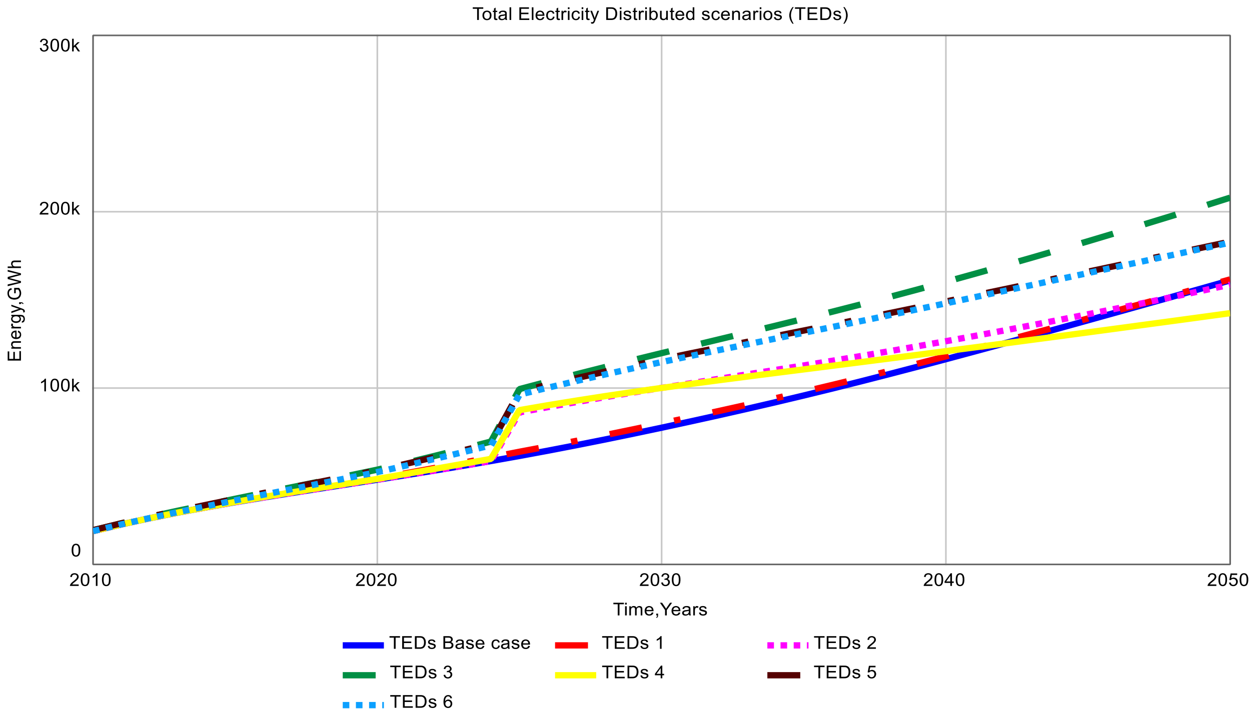


Figure 4.1.2. Electricity distributed scenarios (EDs).

Interestingly, TEDs 3 recorded the highest value of electricity distributed, an approximate value of 208 TWh, followed by TEDs 5 and 6, in that order. Compared to the base case at 161 TWh and TEDs 4 at 142 TWh by the end of the simulation. Nevertheless, TEDs 3 was the highest.

TEDs 3 recording highest value in electricity distributed over the simulation period could be attributed to the following factors: a) some low transmission losses in the system; b) an earlier adjustment in TAC of 15 years; and c) an increasing population growth rate among other factors.

4.2 Electricity per capita

Results of electricity consumption per capita and electricity demand per capita were shown. These quantities helped to illustrate the contributions and impacts of various scenarios on electricity per capita. The unit were given in kilowatt-hour per capita (KWh per capita).

4.2.1 Electricity Consumption per capita (ECCs)

Figure 4.2.1 shows graph of electricity consumption per capita for scenarios 1 through 6; these values were represented by ECCs 1 to ECCs 6, in that order.

All scenarios followed the same increasing trend till 2024. It can be observed that the scenario ECCs 5 followed by ECCs 6 showed the highest among other scenarios. Also, it can be seen that the base case scenario and ECCs 1 were observed to be the lowest.

Scenarios ECCs 2, 3, 4, 5, and 6 were observed to have a sharp increase in the electricity consumption per capita in 2024. This was due to the completion and operation of MMPH in 2024. On the contrary, ECCs 1 and base case showed no rise in 2024.

Moreover, a consistent and increasing trend in the per capita were noticed in scenarios ECCs 3, 4, 5, and 6. But a decreasing trend was observed in ECCs 2, merging up with ECCs 1 and the base case scenarios in 2048. This has triggered a further declination of approximate 1.73% and 1.44%, as compared to base case and ECCs 1, respectively. The declination pattern observed in ECCs 2 could be attributable to: i) the high population growth rate, ii) the longer time to adjusting capacities, and/or iii) the lumped transmission losses of 7.5%.

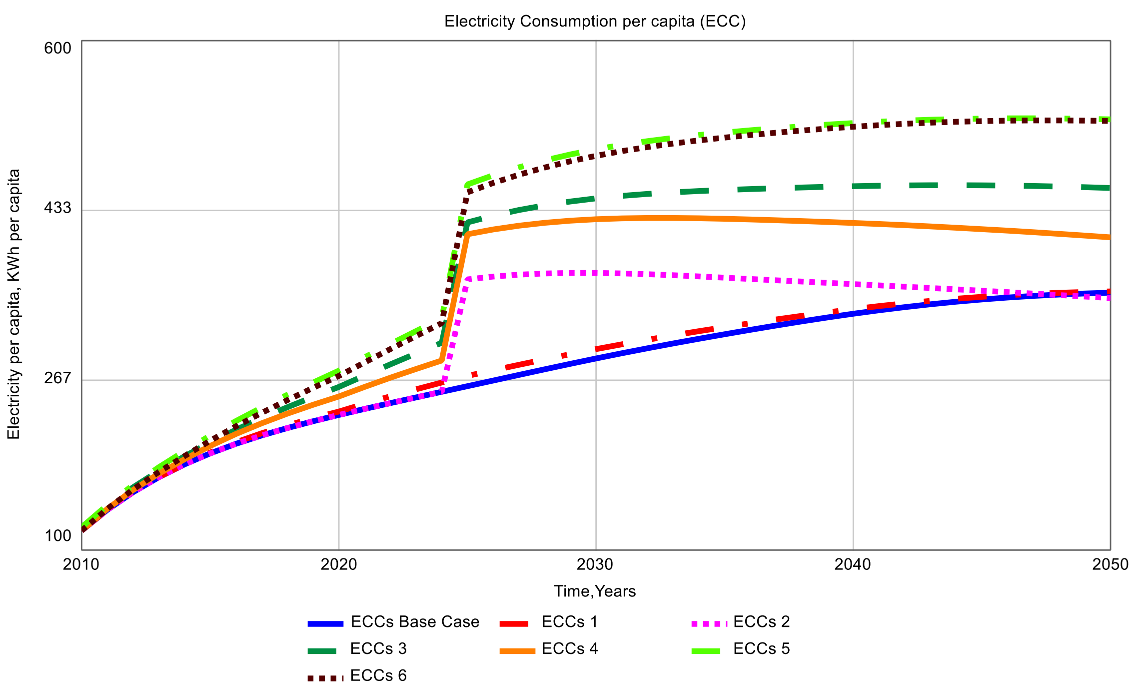


Figure 4.2.1. Electricity Consumption per capita scenarios (ECCs).

However, some scenarios with increasing patterns in figure 4.2.1 were noted at a reduced population growth rate of 2%. Equally, the ECCs 5 buttress this pattern with the highest per capita; it has a TAC of 15%, a Tx of 5%, and a population growth rate of 2%. Therefore, it was clearly affirmed from Figure 4.2.1 that population growth might have been the main driver to electricity consumption per capita in the country.

4.2.2 Electricity Demand Gap (EDG)

Figure 4.2.2 shows ratio between electricity demand per capita and electricity consumed per capita. This ratio is referred to in this study as the electricity demand gap.

a. The demand gap of one (EDGs = 1) suggests that the electricity distributed is just enough to meet the electricity demand at no loss or extra to be stored (unmet);
b. The demand gap at less than one (EDGs < 1) suggests that electricity distributed was in excess. Not only was it greater than electricity demand, but could also be stored for a later usage when it is needed the most.
c. The demand gap greater than one (EDGs > 1) implies that there was an excess electricity demand. Thus, the electricity distributed or supplied was insufficient to meet the rising demand. Therefore, additional energy capacities of alternatives and/or renewable sources must be found to avoid a major collapse of the power system as a whole.

As a result, Figure 4.2.2 explains the various demand gap scenarios as illustrated in the study.

As compared to the trends observed in the previous graphs, Fig. 4.2.2 shows a decreasing trend with EDGs 5. This trend mostly showed a significant deviation as compared to the base case and EDGs 1. The sharp declination was observed in 2024 owing to the completion and operation of the MMPH.

Moreover, the scenarios EDGs 5 and 6 indicated a closer trend to 1 than any other observed behavior. Although none of the scenarios were able to fulfill the demand gap at 1, as illustrated in a) above, but the EDGs 5 and 6 showed closer values of 1.29 and 1.30, respectively, at the end of simulation. The closeness of EDGs 5 to 1 could be attributed to a low population growth rate and a respectively low TAC and Tx compared to the other scenarios.

The inability of all the scenarios to meet the ratio 1 or less than 1 could be an indication that the system under study might be unable to meet the ever growing electricity demand. However, this still requires more close observations.

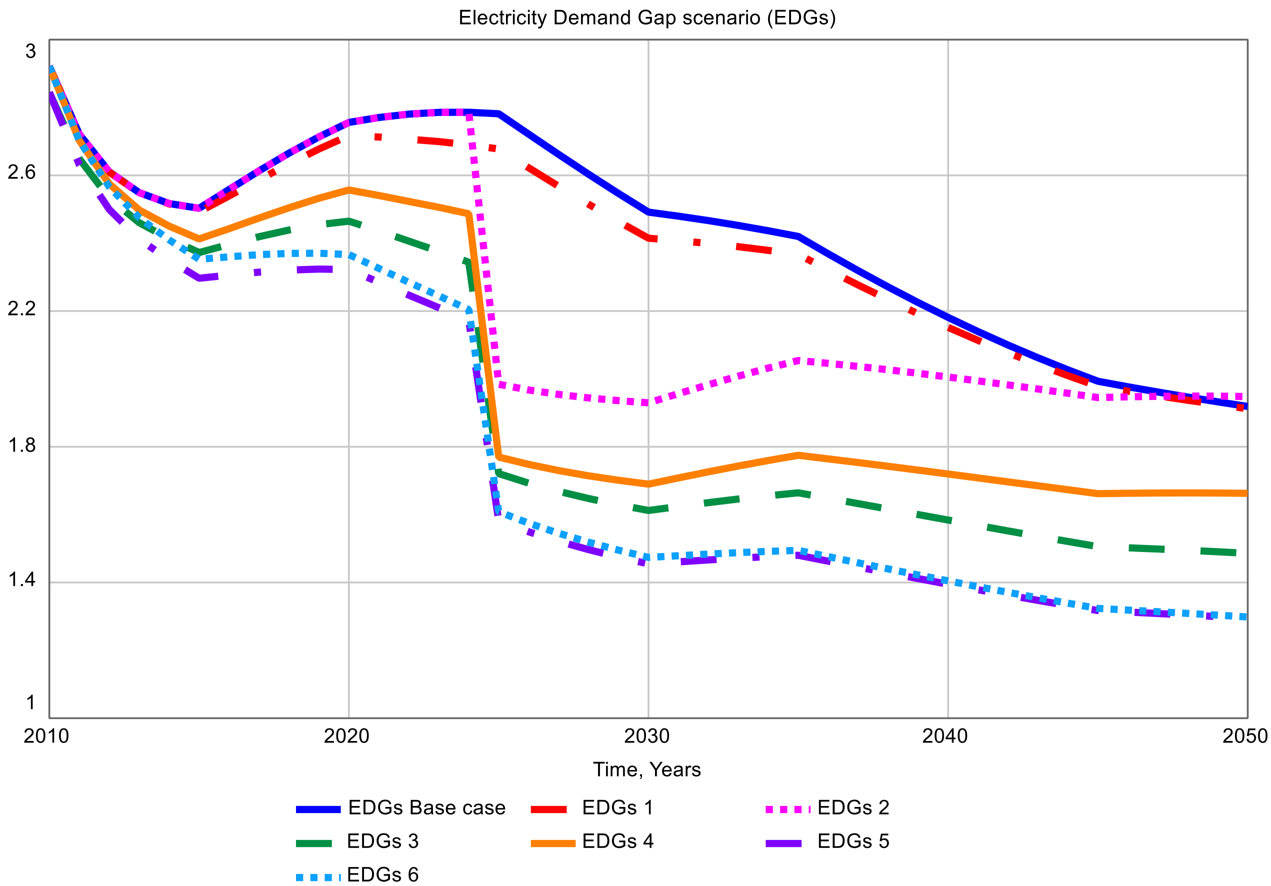


Figure 4.2.2. Electricity Demand Gap scenarios (EDGs).

4.3 Further analysis of the demand gap

The demand gap could be a bases to prove or disprove one of the study's hypothesis. This was a result of effective capacity of the demand gap to show changes in demand and consumption per capita. Considering information from the scenarios, the best fit can be selected for the benefit of all the residents. Further analyses were considered in the variations of the total electricity distributed and per capita electricity demand.

4.3.1 Electricity Distributed vs Electricity Demand

Figure 4.3.1 indicates the variations in the gap between electricity supply and electricity demand. Figure 4.1 above, showed what the trend would have been without the advent of added capacities and adjustment in TAC, Tx, and population growth rate. In addition to the above statement, Fig. 4.3.1 illustrates the contributions of all the scenarios and their economic implications. It is a fact that the relationship between the total electricity supply and demand of any nation is conducive to a social and economic prosperity. Hence, it should be considered that the TEDs 5 option would have supplied 203 TWh at the end of simulation (2050) as compared to 161 TWh that would have been distributed by 2050. Thus, the system, in line with the goals of the study, was able to cover up for 42,000 GWh by 2050.

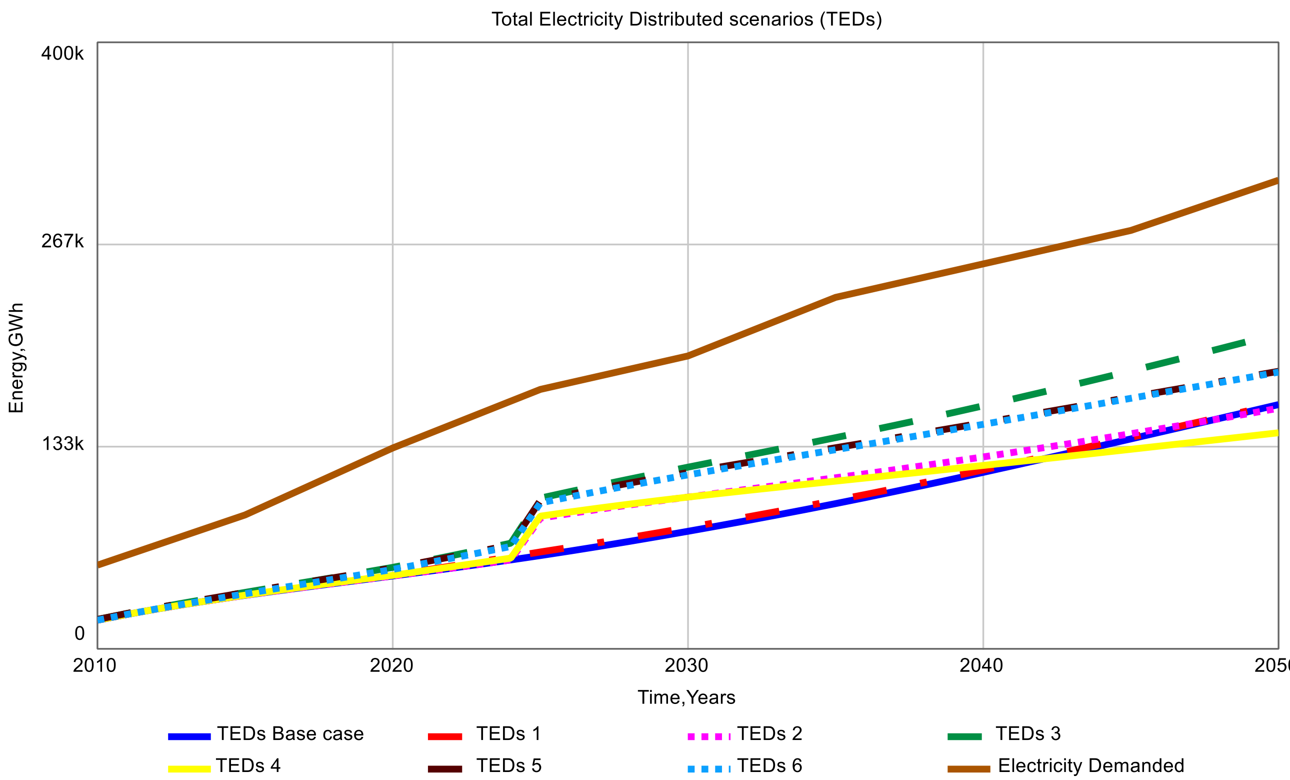


Figure 4.3.1 Electricity distributed scenarios (EDs) Electricity Demand.

4.3.2 Electricity Consumption per capita vs Electricity Demand per capita

Table 4.3.2 portrays the electricity consumption per capita versus electricity demand per capita. This captured the discrepancies between the two parameters. Electricity consumption per capita and demand for the ECCs 5 in 2025 were recorded respectively as 456 KWh per capita and 726 KWh per capita. Thus, a demand of 270 KWh/capita was unmet. This is further explained in Table 4.3.2.

In addition to that, Table 4.3.2 shows the analysis of electricity consumption and demand per capita with its corresponding gap values for all the scenarios, including the base case scenario through the period of simulation (2010 - 2050). It was observed from Table 4.3.2 that the ECCs 5 has the highest consumption per capita and the lowest values in gaps across the years among all other scenarios. These makes the ECCs 5 to stand as a blueprint and can be referred to as an "*improved scenario.*"

Table 4.3.2. Electricity consumption per capita, gaps, and demand per capita

Years	BAU	BAU Gap	ECCs 1	ECCs 1 Gap	ECCs 2	ECCs 2 Gap	ECCs 3	ECCs 3 Gap	ECCs 4	ECCs 4 Gap	ECCs 5	ECCs 5 Gap	ECCs 6	ECCs 6 Gap	Demand per capita
2010	119	223	119	223	119	223	122	220	119	223	122	220	113	229	342
2020	233	408	236	405	233	408	260	381	251	390	276	365	271	370	641
2030	288	430	297	421	372	346	445	273	425	293	493	225	487	231	718
2040	332	392	336	388	361	363	457	267	421	303	519	205	515	209	724
2050	353	324	354	323	347	330	455	222	407	270	532	145	521	156	677

4.4 GHG Emissions

This section reports the life cycle GHG emissions of both fossil fuel sources and RE generating plants. Undoubtedly, the life cycle GHG emission factor of an energy source is a paramount key to estimating the corresponding carbon footprints. Also, a consideration was given to the fuel type as far as the fossil fuel plants are concerned.

4.4.1 GHG emissions from the existing plants

Table 4.4.1 presents the GHG emissions from the current generating plants in the NEPS. The proportion of electricity generation from natural gas (NG) was approximately 75%, while that from hydropower (HP) was 25%. It is obviously seen from Table 4.4.1 that the emissions caused by NG outshines that caused by HP, thus the discovery is in line with the existing technology.

Table 4.4.1. GHG emissions of the existing generating plants

Years	Emissions caused by NG (Unit tonnes CO_2e)	Emission caused by HP (Unit tonnes CO_2e)	TOT emissions (Unit tonnes CO_2e)
2010	1,209,858.93	0.37	1,209,859.30
2015	2,316,282.40	0.70	2,316,283.10
2020	3,311,323.69	1.01	3,311,324.70
2025	4,433,919.90	1.35	4,433,921.25
2030	5,755,524.39	1.75	5,755,526.14
2035	7,195,940.21	2.19	7,195,942.40
2040	8,725,037.08	2.65	8,725,039.73
2045	10,257,716.33	3.12	10,257,719.45
2050	11,719,361.37	3.56	11,719,364.93

4.4.2 GHG Emissions from added capacities

The added supply capacities include coal plants, photovoltaic, small & medium hydropower, and wind energy.

Hence, Fig. 4.4.2a compares the emissions from added capacities. This was achieved by comparing the emissions from coal plant to the other renewable energy sources considered in this study. But This analysis excluded the emissions of the future MMPH.

Moreover, the emissions from the coal power plant was found to surpass that caused by the combine RE sources in the study; it can be seen in Figure 4.4.2a.

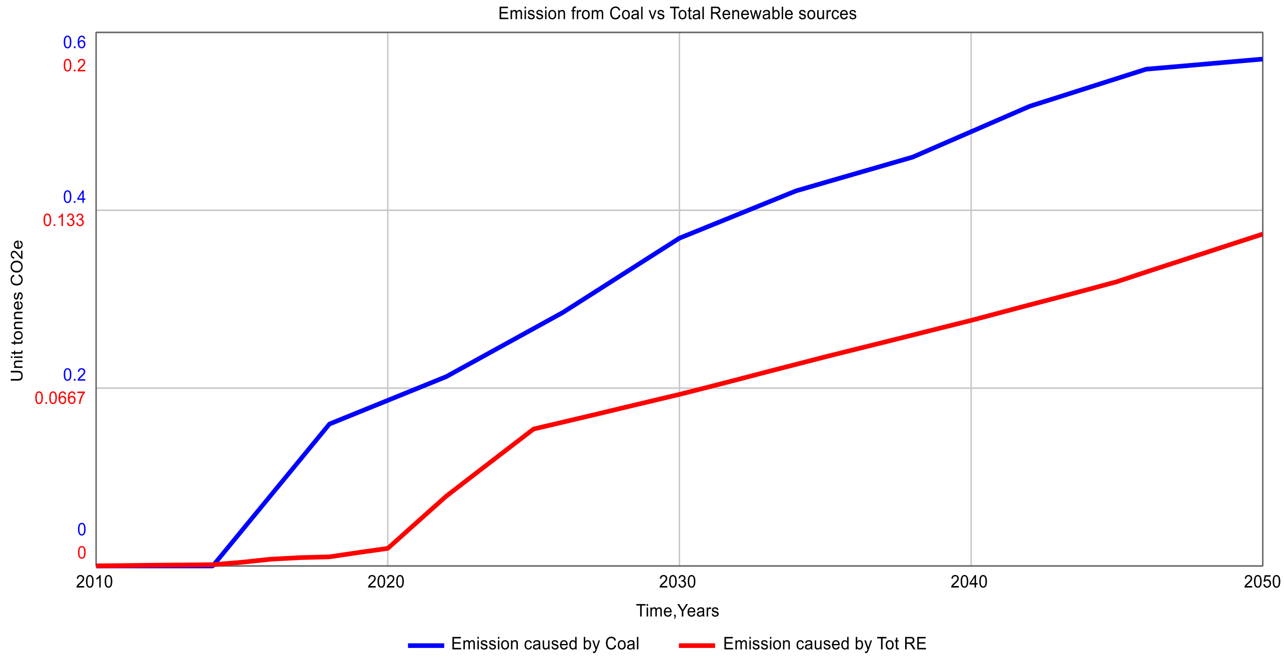


Figure 4.4.2a. Emissions caused by Coal plants and combine RE.

Furthermore, Figure 4.4.2b shows the emissions caused by the projected MMPH considering its full operation in 2024. These hydropower emissions are as well compared with that of the other RE sources and coal plant. It was observed that the emissions caused by the MMPH surpass that of the other sources. The reason is solely attributable to its large generating capacity, which is far more than the capacity of the coal plant. However, in the long run, the emissions from coal would equate that from the MMPH, as the latter is a renewable source of energy.

It is worthy of note that if the same generating capacity of MMPH were the same as that of coal plant, the emissions produced by the latter would have been far larger than that of the former. Thus, the higher the capacity of coal fuel plant, the higher the corresponding emissions compared to the same unit of electricity generated from hydropower plants.

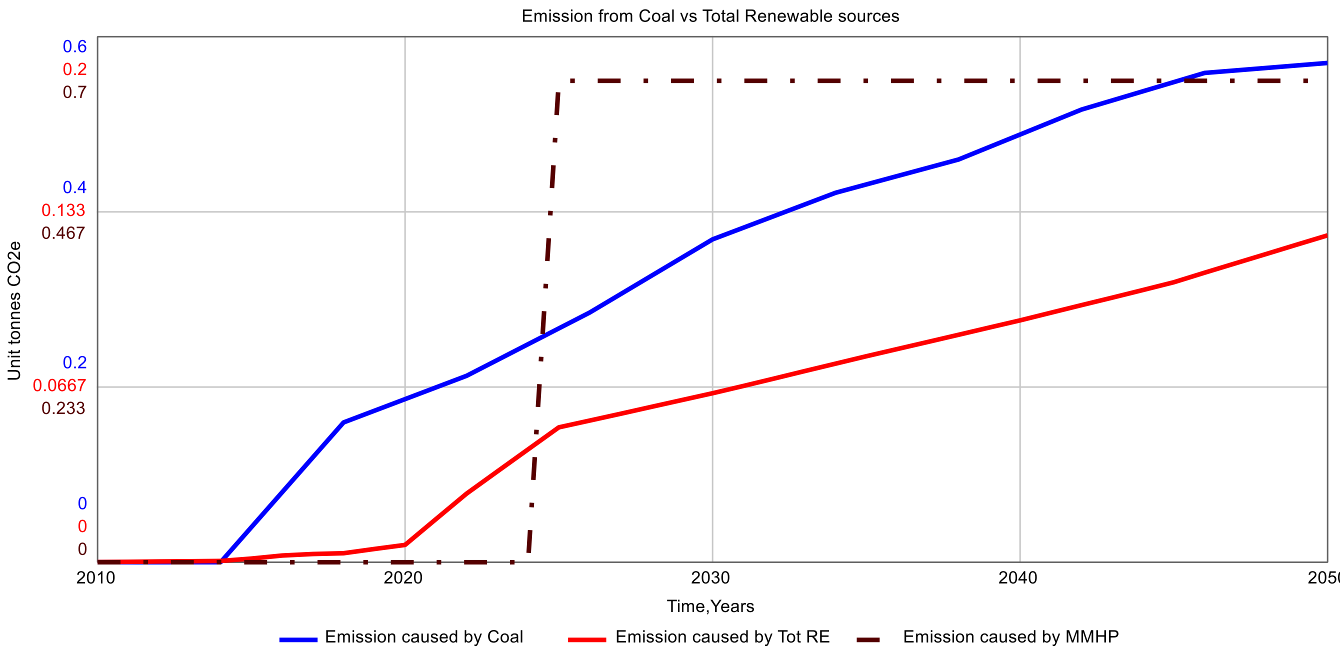


Figure 4.4.2b. Emissions caused by MMPH, Coal and combine RE.

4.4.3 GHG emissions from the theoretical study and existing plants

Figure 4.4.3 represents the simulated GHG emissions caused by electricity generation from all the plants considered in this theoretical study and the existing electricity capacity in the NEPS. Hence, the emissions from the existing plants were found to be very high in Millions tonnes of CO_2e (Mte) compared to the CO_2e quantities obtained from the study. This is due to a higher proportion of NG fuel plants in the NPS energy mix.

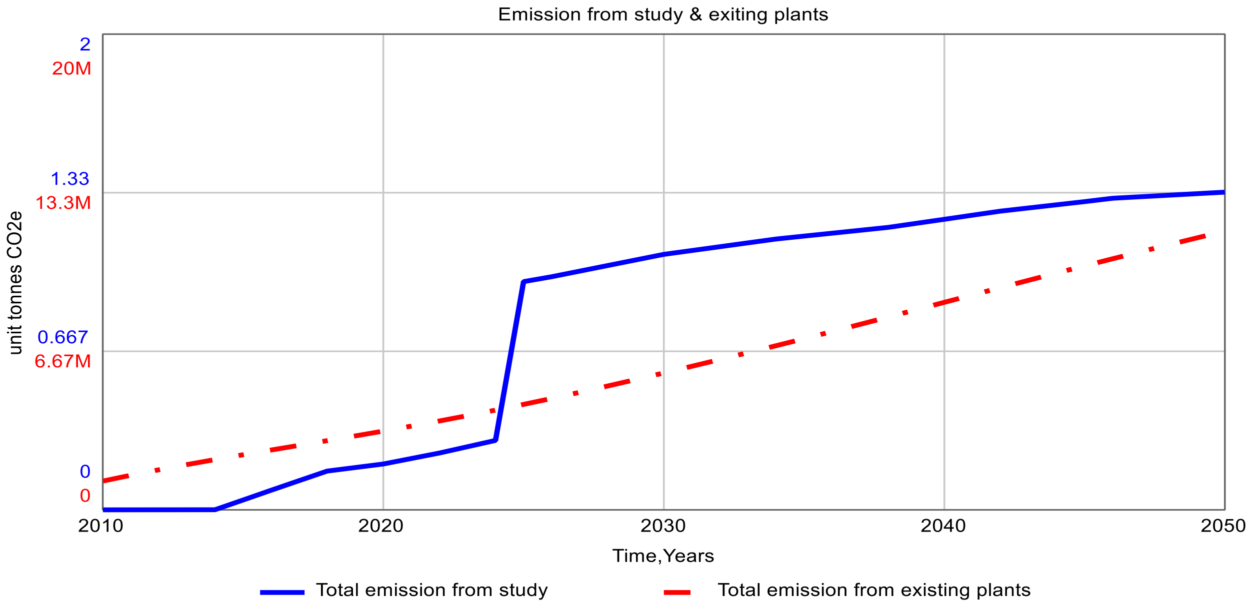


Figure 4.4.3a. Emission from study and existing plants.

Finally, Fig. 4.4.3b shows the total combined emissions from the study (coal plants, photovoltaic, small & medium hydropower, and wind energy) and the existing generating plants. It is observed that the total combined emissions followed the same pattern as that observed by the emissions from the existing plants. This implies only that a small amount of GHG emissions is generated from the study, thus making the project environmentally sound and economically viable.

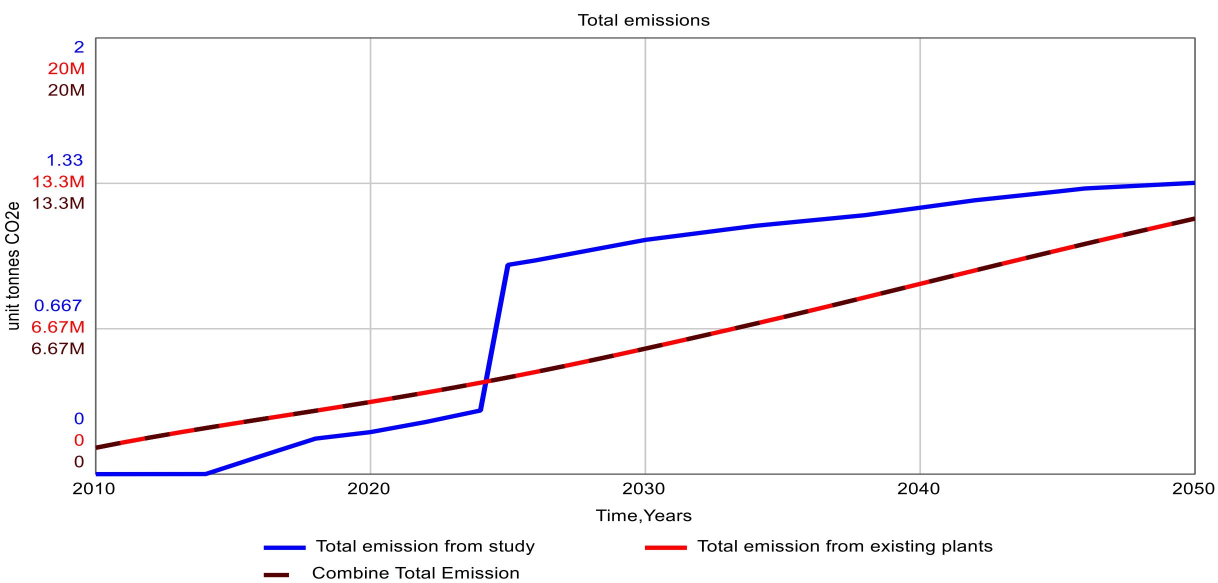


Figure 4.4.3b. Total combined emission.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.0 Conclusion

Nigeria is currently among the fastest growing economy in Africa. Its power generation capacity remains one of its greatest challenges impeding the developmental processes of the country. For a country with such a teeming population and an ever-growing economic development, it is expected that electricity generation remains the main interest for its sustainable development. This study has further identified that there is a huge gap between generated electricity for grid-tied supply and electricity demanded. This is in contrast with the electricity demand per capita and consumption per capita. This electricity supply and demand gap is as a result of weak and old transmission and distribution capacity, theft and vandalism of gas pipe lines, and a long-team negligence of electrification project in the power sector. Over the past few years, the situation of power supply in Nigeria has deteriorated. Industries, commercial enterprises, and individuals now rely on self-generated electricity to run their daily business and activities. This situation has compelled most of the industries to relocate to neighboring countries as a result of increased cost of doing business from self-generated electricity.

Therefore, the aim of the research was to develop a system dynamics model of the Nigerian power sector to evaluate electrification project under-construction with emphasis on renewable energy sources. This study also investigated the potential contributions to merging supply-demand gap in the Nigerian power sector, considering equivalent GHG emissions. Additionally, the research theoretical examined the contributions of the MMPH in merging supply-demand gap. The MMPH, once completed, would be one of the largest hydropower plants in Africa. According to the analysis, the following are the concise results to the study: i) an improvement in the total electricity generated and the total electricity distributed were as a result of low transmission losses of 5 % and an earlier time of adjustment in capacity of every 15 years, considering all added capacities were fully operational. Also, the population growth rate of 2.68 % is expected to drive an increase in more electricity generation. Thus, the generated electricity of 219 TWh at the end of 2050 was recorded; ii) an improvement in the per capita electricity due to a control in the population growth rate to about 2 %, an earlier time to adjust capacity, and a reduction in transmission losses; iii) a reduction in the supply-demand gap to nearly less than unity; and iv) emissions from the existing generation plants were found to be higher than the generation capacities under-construction.

It can be inferred from the study that: a) for the electricity generation and distribution to be improved, the transmission losses should be reduced by 0.5 % and earlier time to adjust capacity of 15 years earlier; b) the completion and operation of various electrification projects would go a long way in improving the energy mix in the Nigerian power sector, thus reducing the frequent power cut and load shedding by improving the environmental wellbeing and reducing CO_2 emissions, which is the main culprit to global warming; c) the supply-demand gap merges by 71%, this would reasonably improve (a) and also encourages industrialization.

In conclusion, the population growth rate, time to adjust capacity, and transmission losses in the power sector are major factors to be considered in electrification processes and planning. Also, the utilization of renewable resources for power generation significantly reduces CO_2 emissions. Finally, the study was able to ascertain that SD modelling approach is an effective tool and methodology to evaluating feedback loops in the Nigerian power sector.

5.1 Recommendations

To resolve the unpleasant situation of electricity insufficiencies in the Nigerian power sector, the study not only advises, but also makes the following recommendations:

I. **Decentralize generated electricity**: power generation should be decentralized. This requires exploitation of energy resources available to different regions of Nigeria for the purpose of electricity generation and utilization in such a way to complement what is being generated. The power generation autonomy of the various regions and states is strictly linked to the use of the available local resources, both renewable and nonrenewable, to generate electricity in a regulated manner.

II. **Research and development**: encouragement of research and development is keen to improving innovation in the deployment and use of renewable energy sources by establishing effective energy research and innovation centers across the nation. As renewable energy sources are easily to put-up and install in a short period of time. Also, its mode of management is not as complicated as that of fossil fuel resources and renewables are environmentally friendly. Research, at various pilot stage should be made available at all level of education.

III. **Training and retraining:** build local expertise in the field of energy planning in order to address a full range of energy issues by encouraging early investment in energy issues. Early investment in building capacity ensures short and medium term decisions support to long-term goals.

IV. **Policy**: the desperate situation of the power sector in Nigeria can only be resolved if adequate policies are implemented to attract the green-energy investors to Nigeria.

Strategy need to be set forth to strengthen the relationship between the GENCOS and DISCOS with reliable information from the transmission company (TCN). It is highly important to check and enable adequate measures to theft and pipe line vandals. Thus, proper policy should be in place to chastise the electric facilities' offenders.

Policy should be set to ensure efficient installation of facilities and repair of worn out generating plants. Though population control is complex and sensitive, appropriate policies should be put in place in order to control its geometric growth.

V. **Time to adjust capacity:** Considering time to adjust generating capacities, is required not only in terms of frequent and routine maintenance, proper management, training, and retraining of staff in the power sector is recommended, but also capacity addition. This was identified in the study as completion of electrification projects under construction: the completion of electrification projects under construction will lead the way the improve energy sufficiency in the NPS by 71%, this improvement will largely be as result of completion and operation of the Mambilla Hydro-power project. Thus, a quick intervention is required in this regards.

To bring to fruition Nigerian quest to become one of the leading economies by 2020, it is recommended for Nigeria to increase its power generation capacity in order to improve the electricity access by 80%. The current access to electricity is about 52%, although it is neither reliable nor resilient.

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