Low Carbon Development Strategy for the West African Electricity System: System Dynamic Approach

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Abstract

Infrastructure development including electricity system requires understanding of the trade-offs needed between economic growth versus climate change issues. This provides the context to explore low carbon development (LCD) pathways - with the electricity sector located at the heart of this trajectory. The premise of this study is that whilst large-scale economic development is needed to pull millions of citizens out of abject poverty, business-as-usual approach would exacerbate the problem of climate change with potentially irreversible long-term consequences. The study evaluated planning processes in the WAPP electricity system vis-a-vis LCDS; explored approaches to implementing LCDS options, to stimulate generation adequacy and security of electricity supply system; assessed LCDS regulatory option(s) to sustain LCDSs implementing options for generation adequacy and security of electricity supply; and, assessed the impact of generation adequacy and security of electricity supply against LCDSs on poverty alleviation, food security and security in the country/sub-region. The analysis of the study were premised on SD quantitative modeling

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approach, involving formulation and simulation of spheres and sectors linked to the electric system in the sub-region to form a complex link of feedback, analyzed and weighted as driving or limiting the Member States of ECOWAS LCD agenda.

Keywords: low carbon development, electricity system, WAPP, feedback loop, leverage points

Introduction

West Africa member states including Nigeria needs rapid transformation to enhance the standard of living of the populace. This will involve adequate provision of needed infrastructure such as energy including electricity for socio-economic development. Nonetheless, achieving this transformation needs ample understanding of the trade-offs between economic growth and development aspiration on the one hand, and climate change issues on the other. Now. it can be argued that the sub-regional desire to develop should precede that of global environmental concern in ranking, however, it is important that this developmental pursuit be done with some sense of responsibility to the environment (UN 1987). Development is energy driven, meaning that energy use drives economic growth and in turn, economic growth drives energy use. As at 2013, the estimated population of West Africa was put at about 322 million with Nigeria contributing over 50% of this; the average annual growth rate is estimated at 2.8 % (World Bank, 2015). Incidentally, countries in the West African sub-region are blessed with abundant supply of various kinds and categories of energy resources though skewed towards some countries like Nigeria, Ghana, and Cote d'Ivoire. Being in the tropic, it is blessed with abundant solar insolation and other renewable energy types coupled with vast reserves of hydrocarbons – coal, oil and natural gas amongst fossil fuel reserves. Despite these vast resources, access to electricity in the sub-region has remained at less than 50% in the urban areas and less than 20% in rural areas.

Relating this to climate change, it is noted that anthropogenic greenhouse gas emissions are mainly driven by population size, economic activity, lifestyle, energy use, land-use patterns, technology and climate policy (IPCC, 2014). This means that if adequate precautions are not taken, even though West Africa sub-region is considered amongst the Non-Annex 1 countries, with her population size, economic activity and energy, the sub-region could well become a prime source for future greenhouse gas emission. With a relatively large population size coupled with the desire to increase electricity generation capacity to meet future demand, it is imperative that sub-region adopt a strategic intervention for her energy consumption agenda. Non-Annex I Parties are mostly developing countries without any obligation to meet any defined emission target under the Kyoto Protocol. Nigeria is one of the Non-Annex I countries. However, according to Gupta et al (2007) though “business-as-usual" are projected for non-Annex I emissions in the absence of any new climate policies to control emissions, however, these projections showed that by 2050, emissions in all non-Annex I regions would need to be substantially reduced below "business-as-usual". Agreeably, there is the need to increase all infrastructural capacity; however this needs to be done with the mind of not repeating pre-industrial age errors of industrialized countries. Thus for West African countries (particularly Nigeria) and any other emerging economies at that, without any strategic intervention, the quest to increase production capacity in the power sector would definitely take the same trajectory as those of developed countries and cause undesired increase in the release of GHG emissions to the atmosphere. The emission of these GHG will occur at levels quite higher than what obtains when compared to its past and current level (IPAM, 2014; Gupta et al 2007; Schneider, 1989).

Climate change is recognized as one of the most complex, multi-faceted, and serious threats the world faces (UNEP, 2011). This recognition gave rise to finding a way to simultaneously address climate change and at the same time help to advance developmental aspirations. Low-carbon development is a development paradigm that contributes to addressing these twin challenges of the 21st century. It seeks to promote economic growth or (sustainable) development while keeping greenhouse gas emissions low, or lower than without interventions. This gave rise to the concept of Low Carbon Development Strategies (LCDS). This strategy, introduced by the Conference of Parties to the United Nations Framework Convention for Climate Change (UNFCCC), represents a common but differentiated approach to meet the overall emissions reduction objectives. LCDS in this way become an overarching framework to design and achieve Nationally Appropriate Mitigation Actions (NAMAs) reflecting the common but differentiated responsibility (CBDR) of all countries. LCDSs have attracted interest in the climate negotiations as a soft alternative to voluntary or obligatory greenhouse gas emission reduction targets in developing countries. Several developing countries have taken the initiative to embark on the process of drafting an LCDS. LCDSs are usually thought of as happening on the country level, but depending on the size or the situation of the country, provincial or sector-specific LCDSs are also possible. Although there is no internationally agreed definition of low-carbon development strategies, this study focuses on integrated climate and (low-carbon) development strategies that cover the intersection of development and greenhouse gas mitigation in West Africa power sector. Adaptation issues included are those that relate to mitigation actions.

Climate change and sub-regional responsibility

COP 19, held in Warsaw in November 2013, Parties to the U.N. Framework Convention on Climate Change (UNFCCC) decided (Decision 1/CP.19) 'to invite all Parties to initiate or intensify domestic preparations for their Intended Nationally Determined Contributions (INDCs), without prejudice to the legal nature of the contributions, in the context of adopting a protocol, another legal instrument or an agreed outcome with legal force under the Convention applicable to all Parties towards achieving the objective of the Convention as set out in its Article 2 and to communicate them well in advance of the twenty-first session of the Conference of the Parties (by the first quarter of 2015 by those Parties ready to do so) in a manner that facilitates the clarity, transparency and understanding of the intended contributions, without prejudice to the legal nature of the contributions'. This decision was reiterated at COP 20, held in Lima 2014 (1/CP.20, 'Lima Call for Climate Action'). Parties also agreed in Lima that INDCs, towards achieving the objective of the Convention, should represent a progression beyond current mitigation efforts and prevent backsliding. The commitment of the Parties to the INDCs is such that countries agreed to publicly outline what actions they intend to take under a global agreement well before the Paris Summit (and for those countries in a position to do so, by March 2015). Their form and rigor will largely determine whether the world achieves an ambitious 2015 agreement and is put on a path toward a low-carbon, climate-resilient future. This study is a first step to developing a rigorous analytical approach to adopting low carbon strategy in the electricity sector of West Africa. A follow up study to the current effort will involve a disaggregation of information used in the model to develop country level strategy. This is to help achieve a platform for country level INDC.

Targeting low carbon economy with the WAPP Electricity System

Without doubt, increasing emissions of greenhouse gas (GHG) have led to a marked increase in atmospheric GHG concentration. A large amount of the increase in atmospheric GHG concentration has been traced to energy related activities. Energy related activities that have brought about the largest growth in global GHG emissions since 1970 are from energy supply sector and transportation. Electricity sector is an energy supply sector that also depends on the use of primary energy sources such as oil, natural gas and coal for its fuel use. Recent study by the World Bank (ESMAP, 2012) on Low Carbon Development shows that by 2035 emissions from energy related activities will contribute more than 80% of total emissions. Also, the recent IPCC Fifth Assessment Synthesis Report (2014) indicates that developing countries or emerging economies cannot afford to rely on business-as-usual approach to climate change related issues.

In West Africa sub-region particularly Nigeria, energy related activities (power and fuel consumption in transport sector) account for more than half (about 55%) of total national emissions (Adegbulugbe, ____, World Bank .....). As would be seen in later part of the study, it is important to state that countries in West Africa are energy deprived and are yet to attain the peak in their energy consumption, meaning that there is propensity to increase emission from energy consumption in the future. IPCC (2014) identifies that anthropogenic greenhouse gas emissions are mainly driven by population size, economic activity, lifestyle, energy use, land-use patterns, technology and climate policy. West African countries are projected to grow at an average rate of 2.8% with economic activity expected to be run at between 6 and 9% annually. In addition, from the economic plan (Vision 2020, Transformation agenda, national economic plan, etc), electricity is expected to play the key role of catalyzing the whole for development process. This means that generation, transmission and distribution sectors of the electricity supply chain are to be expanded to meet anticipated energy demand in the future. The implication is that there will be relative and absolute increase of GHG emissions from the energy sector. That is if the business-as-usual scenario to achieve the growth pathway is taken. However, a low carbon economy approach leaves considerable scope for West African countries to introduce low carbon development strategy that will achieve the same development objectives while at the same time lowering future emissions. Energy related mitigation options that could be examined include: demand-side efficiency improvement options; increased use of renewable energy; supply side energy efficiency options; increased natural gas utilization; use of less carbon-intensive fuel in the transport sector; and transport mode shift to mass transit. This study limits its approach to developing the SD model to examine the complex interactions of the electricity system in achieving low emission option.

Clear Statement of the Problem

Whilst large-scale economic development is needed to pull millions of citizens out of abject poverty, "business-as-usual" approach would exacerbate the problem of climate change with potentially irreversible long-term consequences. West African countries definitely need expertise training in climate risk assessment to fully take advantage of the various international climate change agreements. Current research base shows there are major gaps, which in turn have resulted in relatively low capacity for climate risk assessment as related to infrastructure development. Conceptualizing and implementing low-carbon development strategies have formidable challenges, needing systemic approach; this is a different planning paradigm from what used to be the norm in planning the power sector (World Bank, ___; Momodu, 2012; Olsina, 2005). In line with global expectations it becomes important to develop LCDSs for the power sector, a critical infrastructure in West African sub-region, considering the importance of this infrastructure to economic growth, hence the need for this study. Also, countries in West Africa are member party to the UNFCCC, needing to also meet their obligation of INDCs as agreed in COP19 meeting held at Warsaw, Poland.

Purpose of the Study

Climate change and energy access challenges are arguably the two greatest developmental barriers currently facing African countries including Nigeria. Presently, in Nigeria at least, energy-related activities account for about 55% of total national GHG emissions. Low-carbon development offers ways to link climate mitigation and adaptation with increased energy access. Also, that security of electricity supply will catalyze solution to poverty, food security and security issues. Therefore, the purpose of the proposed study is to identify and test a series of two basic scenarios of low-carbon development options for the power sector in the West African sub-region to contain the level of emission anticipated from the sector in the future. Thus the questions the research attempts to address coupled with the broad objective informed the specific objectives, which are to:

a. evaluate planning processes in the WAPP electricity system vis-a-vis LCDS;
b. identify the global competitive LCD model for the WAPP power sector to stimulate generation adequacy and security of electricity supply system at a rate;

Significance of the Investigation

West African has a population of over 300 million with Nigeria contributing over 50%. Energy use, particularly electricity is projected to rise in the nearest future. At an average economic growth rate of about 6% annually, the demand for electricity is also projected to grow in the same or higher proportion. The implication is not far-fetched in terms of GHG emissions, depending on the choice of the mix of power plants that would be needed to meet the future demand for electricity. There is currently a footprint of power sector in terms of GHG emissions in Wes Africa. This study, based on System Dynamics modeling is however to look at the low emission capacity that could be achieved within the electricity system as related to other spheres and sectors within the economy.

Countries are repositioning the electricity sector to meet global challenges. West African countries are also not left behind as Nigeria had repositioned the power sector from its ‘traditional/vertical integration’ management style to meet with global standard by aiming at improving its unimpressive score sheet of the State Owned Electricity Enterprise (SOEE). Nigeria is currently amongst the highest gas flaring country. To achieve the gas flare-down programme in oil producing areas targets expanding access to hitherto un-served portions of the population in the country and the sub-region. This will also contribute to Nigeria's focus on restructuring and reforming the electricity supply sector as a major priority with the use of the flared gas. West African countries project a future power generation requirements and peak demand at 5.8% annual growth rate[2]. It is inevitable that the sub-region pursues an approach that responds adequately to global climate change obligations as well as meet with this projection of future generation requirements. West Africa is endowed with coal and other hydro resources that could also be increased or added to energy mix which is presently dominated by natural gas and hydro to use for power generation. The West African Power Pool (WAPP) is set up as a cooperation of the national electricity companies in Western Africa under the auspices of the Economic Community of West African States (ECOWAS). The WAPP currently comprise 14 of the 15 member countries of ECOWAS (Benin, Burkina Faso, Cote d'Ivoire, The Gambia, Ghana, Guinea, Guinea Bissau, Liberia, Mali, Niger, Nigeria, Senegal, Sierra Leone and Togo) are working for establishing a reliable power grid for the region and a common market for electricity. The WAPP was

[2] Financed by ODA, a London Economics team in 1991 prepared a least-cost expansion plan for the NEPA system through the year 2011

founded in 2000. WAPP members are made up of private and public power generation, transmission and distribution entities involved in the operations of power network system in West Africa. The model developed examines the generation technologies, the capacity as well as emission from the WAPP (WAPP, 2012). Being looked at as a system, incorporating LCDS in the operations of WAPP was examined to be able to maintain a balance between development and emissions of GHG to the atmosphere. So it is significant to address the critical challenge of the sector to achieve reduced GHG emission and at the same time be developmental in increasing energy access and consumption by developing an acceptable planning paradigm that incorporates acceptable regulatory option(s) for WAPP electricity system to improve standard of living on the long-run; hence the motivation behind the proposed study.

Research Questions or Hypothesis

a. how can the planning process in WAPP electricity system be related to LCDS?
b. what kinds of LCD model are available in the power sector to stimulate generation adequacy and security of electricity supply system at a rate?

The West African Power Pool

WAPP is made up of 14 countries out of the 15 countries. West Africa has an estimated population of 340.6 million, with an average growth rate of 2.7% per annum, ranked amongst the highest in the world. Nigeria alone accounts for over 52% of the total population covering a surface area of only 18% of the estimated size of 5,105 million km^2. The WAPP is an international organization operating in the general interest of the regional power network system with a view of ensuring reliable power supply throughout the region. The WAPP has three objectives, namely:

1. ensure effective and efficient implementation of WAPP priority projects
2. establish a regional electricity market; and
3. capacity building for WAPP.

The WAPP vision is to integrate the national power systems into an unified regional electricity market - with the expectation that such mechanism would over the medium to long term, ensure the citizens of ECOWAS Member States with a stable and reliable electricity supply at competitive costs". The WAPP mission is to "promote and develop infrastructure for power generation and transmission, as well as, to ensure the coordination of electric power exchanges between ECOWAS Members States" (WAPP, 2012).

In terms electricity supply infrastructure, Nigeria dominates the WAPP as shown in Table 1. For WAPP electricity production, Nigeria contributed about 57% to the total of 38,826.6 million kWh that was consumed in 2010 from a total available capacity of 9550 MW out of the 16391.7 MW total installed capacity. The WAPP power system covers two geographical zones A and B, each consisting of interconnected systems, which, according to ECOWAS vision 2015, should be connected together to facilitate electricity trade in the region. WAPP Zone A Member States include Cote d'Ivoire, Ghana, Togo, Nigeria, Niger, Burkina Faso and Benin. They are all presently interconnected under the following border interconnections:

- Cote d'Ivoire - Burkina Faso, Cote-d'Ivoire - Ghana - Togo - Benin - Nigeria: exports emanates mainly from Cote d'Ivoire, Ghana and Nigeria to other countries; however, Ghana imports from Cote d'Ivoire.
- Nigeria - Niger: the bulk of electricity needs to Niger are met by supply from Nigeria.

Table 1 Electricity supply structure of the WAPP

Country	Generation, transmission and distribution	Electricity production (million kWh)[3]	% contribution
Benin	Société Béninoise d'Énergie Électrique and Communauté Électrique du Bénin	124	0.3
Burkina Faso	Société Nationale d'électricité du Burkina Faso	611.6	1.6
Côte d'Ivoire	Société de Gestion du Patrimoine du Secteur de l'Electricité (SOGEPE)	5,275	13.5
The Gambia	National Water and Electricity	160	0.4

	Company (NAWEC)		
Ghana	Volta River Authority and Electricity Company of Ghana	6,746	17.3
Guinea	Electricité de Guinée	850	2.2
Guinea Bissau	Electricidade e Aguas da Guine-Bissau	65	0.2
Liberia	Liberian Electricity Corporation	350	0.9
Mali	Energie du Mali	515	1.3
Niger	Société Nigérienne d'Électricité" (NIGELEC)	397	1.0
Nigeria	Various companies	21,920	56.2
Senegal	Société d'Électricité du Sénégal	1,880	4.8
Sierra Leone	National Power Authority (Sierra Leone)	80	0.2
Togo	Togo Electricité and Communauté Électrique du Bénin	0	0.0
	Total	38,973.6	

Regional strategic resources for electricity production

The major strategic resources available for electricity generation in the West African region include crude oil, coal, natural gas and hydro power. Coal is used as a very low quantity in Niger Republic. Some countries already have biomass in their energy mix while in some other instances, there are plans in the pipeline to include renewable energy sources, aside from hydropower, to be incorporated into the energy mix of some nations like Nigeria and Ghana (Tractebel Engineering, 2011; WAPP, 2014).

Electric power system planning

Literature (Hertzmark, 2007; Chernick and Wallach, 1996; USEPA, 2006) reveals that there are quite a number of approaches adopted in planning for solving utility problems, but the common approach had been to link a series of departmental models together (Ford, 1997). For a large, well staffed utility, the modeling system developed might be up to 30 or more. In order to run the model, it takes a set of electric rates needed as input to a demand model. In turn, the output of the demand model takes the form of electric load for each of 20 years in the future. These results are then fed to a capacity expansion model. The output of the expansion model is then shown as a plan for new power plant construction during the 20 year planning period. This plan would form the input for a third model to calculate the utility revenue requirements and electric rates. The electric rates at the end of the process are then compared with the rates used to start the modeling. If the two sets of rates are significantly different, the utility analysts might adjust the input rates and repeat the entire sequence of calculations. Through artful manipulation of the starting rates, the iteration of the model run might result in a consistent set of projections with a small number of reruns.

The existing models were often developed in separate departments and usually grow to be quite complex in order to serve each department's need for detail. These models were sometimes implemented in different programming languages, and sometimes reside on different computers, depending on the needs of each department. The iterative approach has a principal drawback in the length of time interval required to prepare and complete an internally consistent set of projections. In practical terms, the iterative approach seldom resulted in a consistent set of projections. The more common approach was simply to ignore the inconsistencies that arose from the lack of information feedback within the system.

Approach to modeling of long-term electric power markets

Long-term modeling approach by participating firms in electric power markets are usually with the use of optimization-based techniques (Hertzmark, 2007). When the formulation of this technique is based on the assumption of optimal resource allocation, it is known as partial equilibrium model. The assumption usually made is that the perfect competition is "perfect", and incumbent firms will behave rationally. These kinds are currently focused predominantly on the short term, even though some few long-term markets based on optimization techniques exist. These latter techniques are formulated on the assumption that resource allocation resulting from the market mechanism is equivalent to the minimization of the discounted, cumulated, operating and investments costs over the considered planning horizon. It is important to also point out that there are optimization based models that do not rely on the assumption of perfect competition (Vits, et al. 2007). Mirzaesmaeeli (2007) developed multi-period optimization model for energy planning with CO_2 considerations. The model was formulated using an objective function that minimizes the net present value of the cost of electricity (COE) over a time horizon of 14 years. This model could be classified as a medium term model based on its time horizon. Further work on kinds of available optimization models for the analysis of electric power market performance can be found in Ventosa et al (2005).

Generally, optimization-based models present ***prescriptive*** approach of the system it analyzes (Biswas, 2008, Olsina, 2005)**.** They describe the behaviour of the system under ideal condition, though this description may not always be verifiable in true or real markets. Their advantage stems from there serving principally as benchmarks on what the market behaviour should do. For their mathematical solution however, this model usually needs important simplifications. However, one major limitation to these models is that they commonly neglect the existence of feedback and time constants in the systems being examined. The implication of this neglect is that under this modelling approach, the system response or performance is viewed only as a sequence of stable and optimal long-run equilibrium state.

On the other hand, the econometric and simulative models are inherently descriptive, that is, they describe outputs of phenomena of interest, e.g., will the building collapse in an earthquake? If I follow this course of action, what will happen? In terms of electric power modelling however, econometrics approach has not been so extensively applied to long-term performance. Even though quite a number of reasons could be adduced for this, the principal one that could deduced is that dealing with dynamic systems will be difficult using static relationship and not by means of market fundamentals. Literature reveals that these models are instead applied to long-term demand forecasting related to other fundamental parameters such as population and economic growth, energy prices etc. Good examples of such approach are the model presented by Lo et al. (1991) and Chern and Just (1982).

Unlike the econometric models, simulative models currently enjoy an increased interest for their flexibility in modelling the actual behaviour of power markets. One principal advantage they have is their suitability for capturing soft characteristics present in real markets like bounded rationality, learning abilities, information asymmetries, etc (Ventosa et al., 2005). There are presently two separate streams of literature covering the development of simulation methods.

Firstly, is the modelling discipline grounded on the system theory and control engineering and applied mainly to business and managerial systems. This modelling discipline is known as system dynamics (SD) and is focused on the macroscopic structure of the system under study. It also deals with the interrelationships among the systems' components in order to explain the dynamical behaviour. This approach implies the formulation of the differential equation representing the time response of system variables, which generally describes attributes at an aggregate level. Bunn and Larsen (1992) and Ford (1999) have presented pioneering works showing in a very simplified version the first casual-loop diagrams of a liberalized power market describing the dynamical terms of the market balancing mechanism responsible for maintaining adequate supply reliability levels. The limitations of these studies as observed by Olsina (2005), is that they did not present the mathematical formulation and characterization of the dynamical state equation representing the power market.

Agent-Based Modelling (ABM) is the second and more recent modelling approach in the computational and simulation. This is at the micro and unattached (*corpuscular*) level though seems to be a modelling discipline gaining significant attention. Most of the attraction of this approach is based on the possibility to model heterogeneity, autonomy and individuality (Olsina 2005; Macal and North, 2006). Agents pose some rational limitations in the decision making rules they use but exhibit some abilities to learn from the environment. The aggregate system behaviour emerges from the interaction among the elemental and evolving entities. Though, these two approaches are radically different perspectives, SD and ABM models must deliver equivalent descriptions of the systems at the aggregate levels. Currently, the relationships between both approaches are intensively investigated (Borschev and Filippov 2004; Pourdehnad et al., 2002; Scholl, 2001).

The flexibility of the SD model informed its selection to model the long-term performance of WAPP electric power system particularly considering superimposing LCDS to it. By its definition, the quantitative modeling approach using SD principles will allow this study to query various likely courses of actions (LCD models) in a computer-based model.

System boundary and general research approach

The electric power system is characterized as a structural model (Olsina, 2005), having a bottom-up approach, since the long-run development of the power market is determined by modelling the variables having direct influence on long-term movements of supply and demand. Figure 1 presents a simple description of the Nigeria electric power market showing the competitive and regulated segments respectively. Figure 2 shows the interconnection in the WAPP. Nigeria is currently the only country in the sub-region that has unbundled the electricity system while others are still bundled as vertically integrated system. It is for this reason that Nigeria was used example. In the system, the competitive segment is made up of the generation and retail sectors as depicted by the 6 generation companies, 4 independent power producers (2 of which are for state governments) and 11 distribution companies to also include the customers while the regulated segment is made up of the 'wired' sector namely the transmission and distribution networks. For the WAPP interconnections, the regulatory arrangement is such that ERERA, as the specialized institution of ECOWAS, has the main objective of regulating interstate electricity exchanges and to also give appropriate support to national regulatory bodies or entities of the Member States. So ERERA handles interstate regulation in the 'wired segment' of the WAPP), functioning presently as the WAPP Market/System Operator handling interstate power exchange, while national entities are responsible for the Market/System Operation within the national boundary until an Independent Market operator is created out of WAPP that will be primarily responsible for the implementation of the Market Rules. For Nigeria, the regulatory functions in the electricity system is under the control of the Nigerian Electricity Regulatory Commission (NERC).

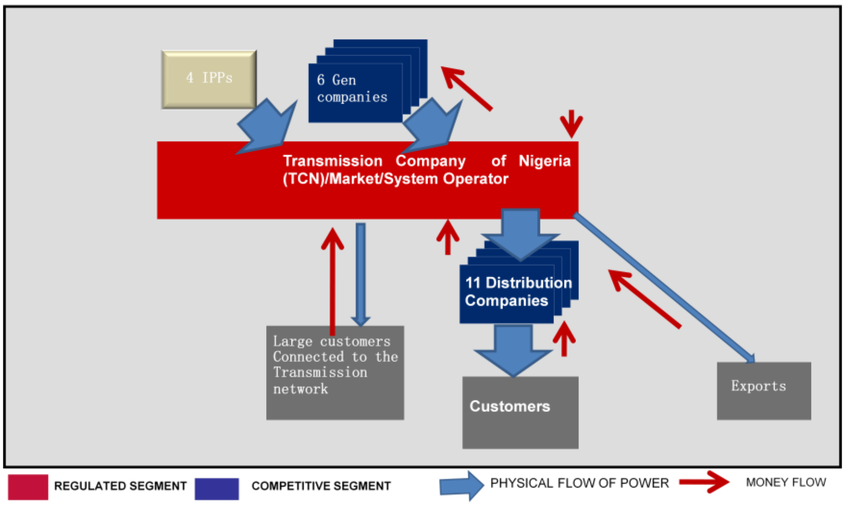

Figure 1 Simple flow chart of the competitive and regulated segments of the Nigeria Electric Power System (NEPS) as described by the EPSR Act 2005

In WAPP system, there is the Regional Market Rules that are basically a set of commercial Rules to govern the roles of all markets participants including the buyers, sellers, and System operators and is overseen by ERERA as Regulator. The Market Rules were developed by WAPP and approved by ERERA after wide consultations with all stakeholders. Its scope is more of a commercial and legal nature as it also contains provisions for electricity trading and dispute resolution, the latter task will be undertaken by ERERA where there are disputes between market participants. The Grid Code on the other hand is the set of rules that are purely technical in nature specifying the technical requirements for the regional transmission grid. Again this document was developed by WAPP and approved by ERERA but WAPP has the primary responsibility of enforcing and overseeing its implementation. Together with the Operational Manual which focuses more on system control and dispatch, the Markets Rules and the Grid Code make up the basic set of Rules for the effective operation of the Regional Electricity Market.

In order to demonstrate the simulation focus, the required inputs, and the system boundary of the research approach, a bull's eye diagram of the model as adapted from Kilanc and Or (2008) is presented in Figure 3. In the bull's eye diagram, endogenous variables are placed in the center of the bull's eye; exogenous variables are placed in the outer frame. Excluded variables are placed outside the outer frame. The bull's eye diagram is a convenient way to show the relative balance between required inputs (exogenous variables) and endogenous variables. If endogenous variables are more, this is a good sign indicating that ''model generates interesting dynamic behaviour from within the system'' (Ford, 1999). If a variable appears somewhere in a feedback loop, or it is influenced by another variable that it is in a feedback loop, then the related variable is said to be an endogenous variable in the model.

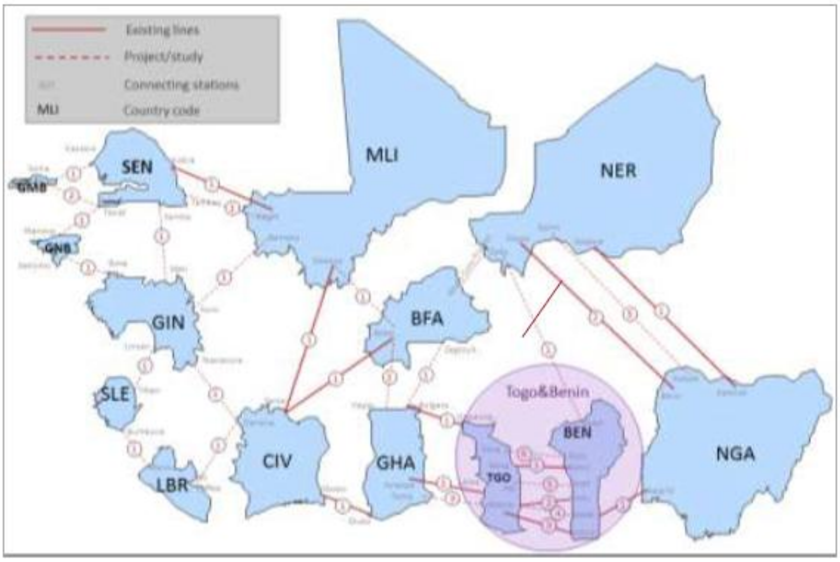

Figure 2 The interconnections in the WAPP

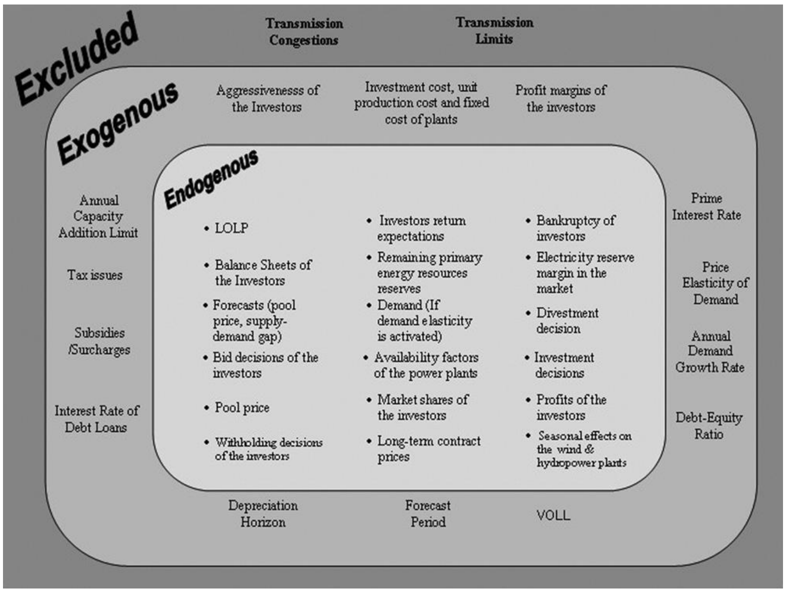

Figure 3 Bull's eye diagram of the model (adapted from Kilanc and Or, 2008)

Conceptual framework

The conceptual framework was developed for analysis of the data elicited, using of feedback control system based on SD principles as depicted in Figure 4 in its canonical form. Each of the variables, namely, R(s), G(s), C(s), and H(s) in the system (Figure 4) is explained. Figure 5 shows the block schematic diagram for the study while Figure 6 shows the interconnectivity of the sub-systems of economic, LCD and power sector evaluation.

R(s) in the system is the input which represents a superimposed LCD model to reduce emission from the projected increment in national electricity consumption level. This will come from evaluation of a combination of the various available LCD models, projected economic growth rate and INDC for the country that will allow for sustainable development. It is important to point out that before liberalising the electricity sector, demand in the sector was not market driven but rather by arbitrary government pronouncement which could have accounted for the suppress demand in the system amongst other factors. Hopefully, with liberalization of the system, the suppress demand could be reduced or eliminated.

LCDS imposition on the power system in Nigeria and the WAPP is expected to generate new regulations and rules (bureaucracy) that may demand new or modified organizational structures such as regulators (NERC), investors (IPPs), government involvement (FMP and ECN) and the PIPES (Planning, Investment, Programming and Environmental Safeguard) Department in the WAPP Secretariat. for implementation. G(s) had earlier been defined as the aggregation of the supply side of the system under study which consists of generation, transmission, distribution system operation and retail trading. G(s) is thus the aggregation of the supply side, which includes generation, transmission/system operations and distribution available in the power system. Also, the output is **C(s)** is described as the performance of the utility as measured by the electric power demand met measured in GWh through the generation capacity measured in MW. **H(s)** represents reduced GHG emission and INDC for the power sector.

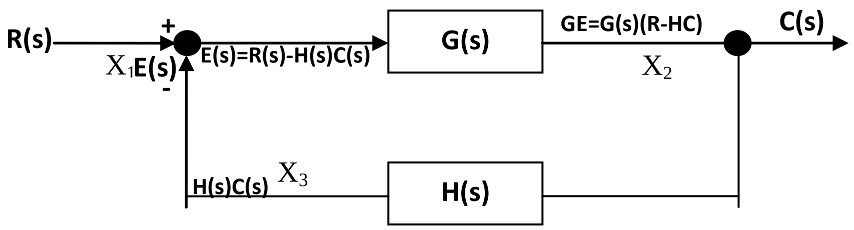

Figure 4 A closed-loop control systems (AIEE, 1951)

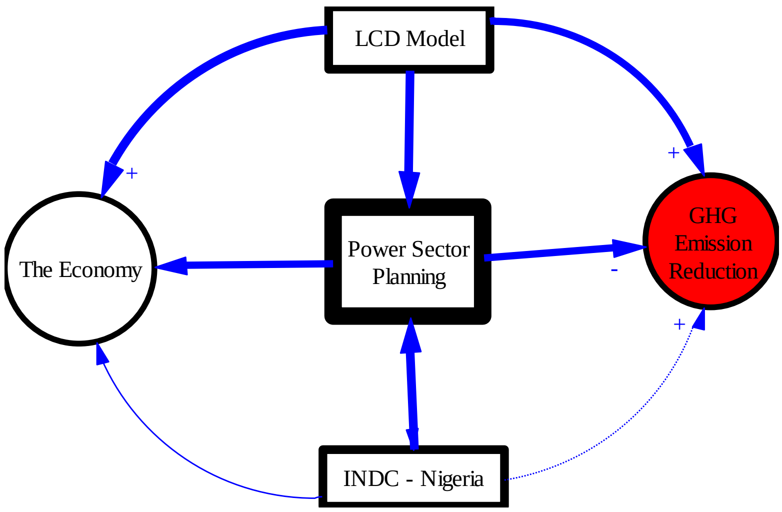

Figure 5 Block schematic diagram of the study conceptual framework

Based on the canonical form of the feedback control system, the causal loop diagram for the conceptual framework proposed to be used in the study is as presented in Figure 3.

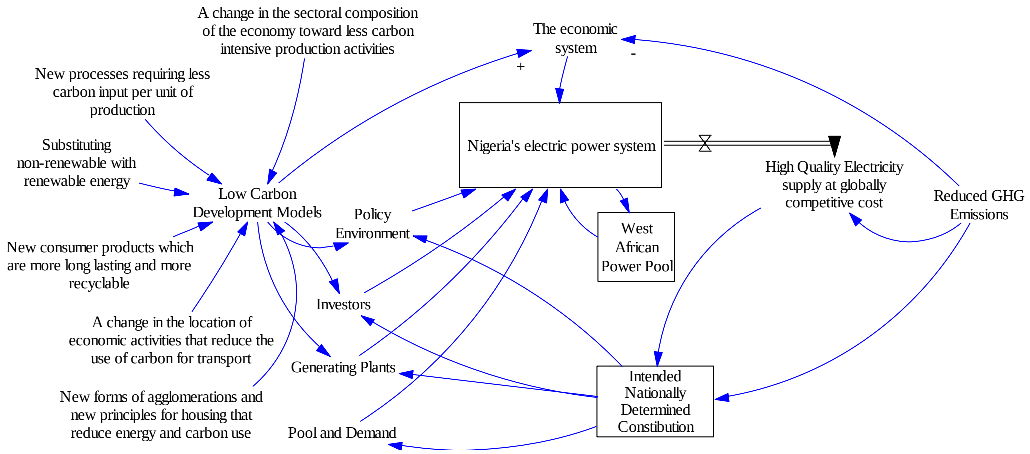

Figure 6 Causal loop diagram depicting study conceptual framework

LCDS and Power Sector Analysis

Since the study is limited to the power sector alone, the options considered were limited to: alternatives to current generation technologies and reduction in Transmission and Distribution Losses. Other options like demand side management to reduce emission in the electricity system is looked at in another study. These are presented in Table 3 and are incorporated to the model as LCDS.

Table 3 Options Considered for Low-Carbon Strategy in WAPP Electricity System

Low-Carbon Technology	Reference Technology	Remark
Off-grid hybrid-wind-diesel	Off-grid diesel gen	Generation technology
Off-grid solar PV	Off-grid diesel gen	Generation technology
Small hydropower	Off-grid diesel gen	Generation technology
Wind turbines	SCGT	Generation technology
Concentrating solar thermal power (CSP)	SCGT	Generation technology
Solar PV (grid)	SCGT	Generation technology
Biomass	SCGT	Generation technology
Hydropower	SCGT	Generation technology
Supercritical coal with CCS	Subcritical coal	Generation technology
CCGT	SCGT	Generation technology
EE CFL lighting (grid)	Incandescent lighting	Demand side management
EE CFL lighting (off-grid)	Incandescent lighting	Demand side management
T & D Losses	Improved system operations	T & D

Source: World Bank (2013)

Methodology

The framework for this study is based on achieving low carbon development strategy for the power sector in Nigeria. This strategy ultimately meant to be adapted as the Nationally Appropriate Mitigation Action (NAMA) for sub-regional and country level response to the Commonly But Differentiated Responsibility (CBDR) in combating global climate change. The most important outcome of the study using the model for analysis is to develop a platform that will make electricity system in West Africa an ambitious, transparent and equitable one in being able to attract investments in a timely manner to increase the generation capacity through more efficient technologies. As a follow-up to that in Momodu (2012), the study relied on both primary and secondary data sources to elicit required information. Primary data were sourced from through the use of questionnaire instrument administered to the relevant authorities in the West African sub-region on electricity industry. Variables related to electricity market model development were used to develop the questionnaire. Secondary data were sourced from various electricity market model development and regulatory approaches. The developed model, a quantitative one (Zagonel and Corbet, 2006), formed the principal means of arranging the complexities in the West African electricity system and was used to conduct the analysis after the basic interconnecting structure of the system was established in the model.

Research Design and Procedures

The design of the study took the following into consideration. First step involves the capture of data that are useful for electricity planning and management in West Africa electricity sysrtem from secondary sources for the period under review. Primary data were sourced from the regional bodies responsible for electricity development in the sub-region, namely, WAPP, ERERA and ECREEE. WAPP and ERERA were the main responded to queries concerning their operations. Other sources were used to supplement data from the primary sources. Data collection were done using the application of partially structured questionnaire (Johnson and Wichern, 1997). Data analysis will be carried out using descriptive and inferential statistics, where necessary. A combination of the outcome of these exercises, including low carbon development strategy is to form key inputs for examining long-term performance of the WAPP. The timeframe for examining the system was 50 years starting from 2011.

Model development

The System Dynamics model conceptualization was based on Zagonel and Corbet (2006) and Sterman (2000). Its structure was developed based on a review of the operations of the WAPP electricity system. EP-LCD model is organized in spheres and sectors and was customized following a modular approach. The EP-LCD model is largely focused on electricity operations and interconnections in the WAPP power system particularly the generation technologies. Table 4 shows all of its spheres and sectors (with sectors being the building blocks of the higher level aggregation represented by the spheres).

The structure of the model was developed based on the objective 2 of the WAPP as well as WAPP's vision and mission that aims to make the electricity system in the ECOWAS sub-region to be operated as a merchant power market when enabling environments for this kind of operations is achieved (WAPP, 2012). The capacity addition component in the system can be represented in two ways to explain the dynamics of the electric power markets and had been well described in Olsina (2005), Graham and Fubanks (2003, and Musango et al., (2009). These two representations are its causal-loop, and the stock-and-flow diagramming respectively. These two representations thus take the present operational conditions of the WAPP into consideration to develop the model for simulating internal behaviour dynamics. This dynamics is described by a set of non-linear differential equations that account for existing system feedbacks, delays, stock-and-flow structures and nonlinearities. The EP-LCD model is largely focused on electricity operations and interconnections in the WAPP power system as well as carbon dioxide emitted from the system. Table 3. shows all of its spheres and sectors (with sectors being the building blocks of the higher level aggregation represented by the spheres).

Table 4 Sectors and Spheres in Electricity-Low-Carbon-Development Model

Social and Economic Spheres	Population
	Production
	Government accounts
	Industrial growth
Electricity Sphere	Generation capacity
	Transmission Distribution/Electricity consumption
	Power Demand
	Electricity Marketing
	WAPP
LCD Sphere	New processes requiring less carbon input per unit of production
	Substituting non-renewable with renewable energy
	Energy efficiency target
	GHG mitigation target

EP-LCD model is distinguished by the manner in which various sectors and spheres are linked together to form a complex link of feedback loops in which the electric system can be analyzed and weighted as driving or limiting the county's LCD agenda. Basic feedback structure depicting a simplified causal-loop for electric power system as adopted from Olsina (2005), Graham and Fubanks (2003, and Musango et al., (2009) is presented in Figure 7a and 7b respectively to provide an overview of the system's dynamical structure and to guide further discussions when modeling the different system components. The diagram shows the basic balancing feedback that governs the long-term development of any power market. Market participants form expectation on the future electricity prices on the basis of current market conditions and expected fuel prices as well as future carbon trading prices. These expected prices play crucial role in determining the profitability of possible investment projects. This implies that construction of new power plants is predicated on the assurance that there is enough certainty of investment cost recovery. Therefore, the first delay in the feedback loop is in regard of irreversibility of investment, that is, the investment decision delay, denoted with T_1. In addition to this delay, new power plants are required to get permissions at stipulated LCD standard and they need a certain time to be constructed and to be brought on-line. This forms the second delay on the feedback loop and is denoted in Figure 5 as T_2. The existing capacity plus the additions of new capacity, the scrapping/decommissioning of old power plants and the current system demand will determine the new reserve margin and the new prevailing price level. With this therefore, the market becomes self-balancing and resembles the negative feedback loops commonly encountered in control systems. This balancing mechanism is responsible for maintaining an adequate reserve margin to ensure a reliable electricity supply.

However, this causal-loop-diagram (CLD) is useful to represent the causal relationships and the market balancing feedbacks responsible for adjusting the production capacity, it is not capable to show explicitly stock-and-flow structures embedded in the system. In Figure 5, the stock structure underlying delay T_2 is revealed. This stocks-and-flow-diagram (SFD) shows important variables controlling rates of flow into stocks, making the issue of capacity adjustment mechanisms clearer.

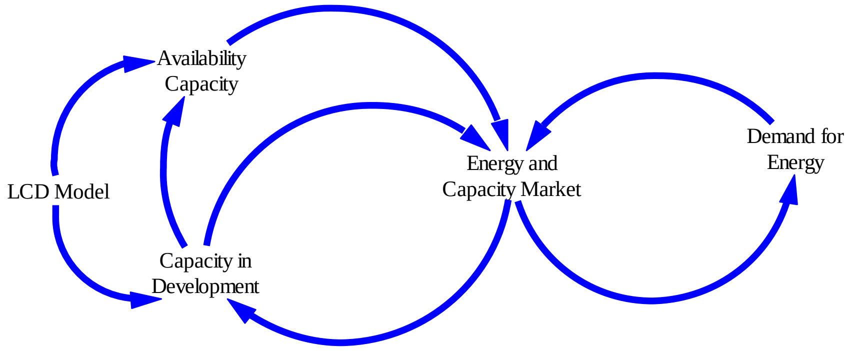

Figure 7a **Basic feedback structure of electricity system with LCD plan**

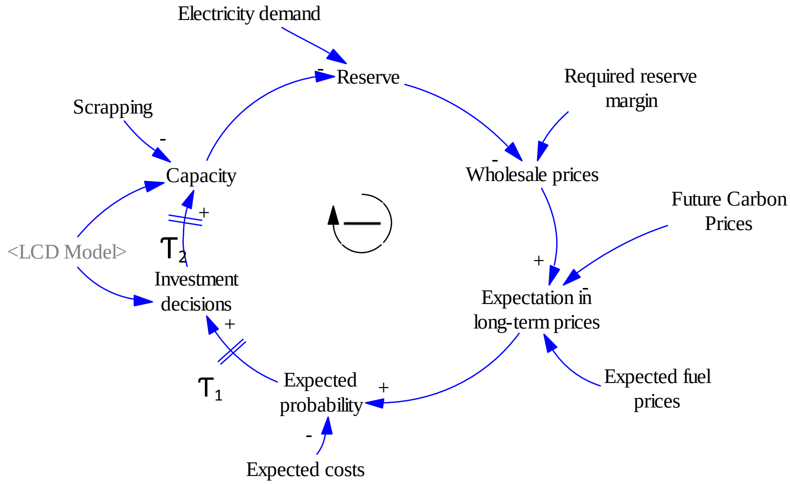

Figure 7b **Causal-Loop Diagram (CLD) of a typical electric power system (adopted from Olsina, 2005)**

Identification of leverage points in the model

Leverage points are places within a complex system (a corporation, an economy, a living body, a city, an ecosystem) where a small shift in one thing can produce big changes in everything (Meadows, 1999). This idea is not unique to systems analysis. Leverage points are points of power in a system that modelers not only believe in but would want to know where they are and how to locate them. According to Forrester (Meadows, 1999) 'leverage points are not intuitive. Or if they are, we intuitively use them backward, systematically worsening whatever problems we are trying to solve.

Meadow identifies the following as places to intervene in a system (in increasing order of effectiveness)

12. Constants, parameters, numbers (such as subsidies, taxes, standards).
11. The sizes of buffers and other stabilizing stocks, relative to their flows.
10. The structure of material stocks and flows (such as transport networks, population age structures).
9. The lengths of delays, relative to the rate of system change.
8. The strength of negative feedback loops, relative to the impacts they are trying to correct against.
7. The gain around driving positive feedback loops.
6. The structure of information flows (who does and does not have access to information).
5. The rules of the system (such as incentives, punishments, constraints).
4. The power to add, change, evolve, or self-organize system structure.
3. The goals of the system.
2. The mindset or paradigm out of which the system — its goals, structure, rules, delays, parameters — arises.
1. The power to transcend paradigms.

Figure 8 is a basic diagram meant to explain parameters, stocks, delays, flows, feedback, and so forth.

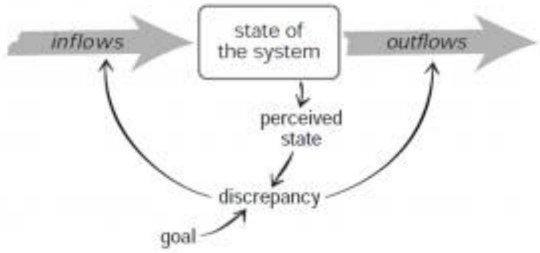

Figure 8 Basic diagram to explain how to identify places to intervene in a model

The “state of the system” in whatever standing stock is of importance — electricity, a nonmaterial commodity. The inflow - electricity generation, investment and financial flow - increase the stock, while the outflow - transmission, distribution, losses and thefts - decrease it. So the bedrock of this system consists of physical stocks and flows, obeying the laws of conservation and accumulation. Now the challenge in the WAPP power system is principally inadequacy; meaning that the inflow rate is lower than the outflow rate, making the non-storable commodity be in shortfall always. It takes time for systems to respond to desired growth as is typical for flows to accumulate. Same thing with the electricity system in WAPP, it will take time to correct the anomalies making it to be sluggish in responding to desired changes. It is critical, however, to be able to identify the 'leverage points' along the line of the operations of the electricity system in WAPP with the superimposed LCD models and the corrective measures to achieve desired objectives as enunciated in the objectives, vision and mission of WAPP.

Systems have at least two negative feedback loops, or correcting loops (Meadows, 1999); one controls the inflow, and the other one controls the outflow, either or both of which can be used to bring the system to a desired level. It is important to point out that the goal and the feedback connections are not visible in the system. But a "long enough watch" over the system will enable one to figure out what are the leverage points in it. Now, our study involves superimposing a new paradigm - LCD - into the planning of an already complex system, the Nigeria electricity system coupled with the WAPP power system to bring out future plan that is responsive to delivering electricity that is globally cost competitive at the same time achieving desired INDCs. Identifying the leverage point in the system cannot be done intuitively but through counterintuitive approach.

Having explained this system theory of identifying leverage points in this study, we did not attempt to explain the places to intervene in a system as this has been fully done in Meadows (1999).

Scenario development and sensitivity analysis

Sensitivity testing is the process of changing your assumptions about the value of constants in the model and examining the resulting output (Ventana, 2013). Parameters of system dynamics models are subject to uncertainty, so sensitivity analysis is an important task for the reliability of simulation results (Hekimoğlu and Barlas, 2010). Since system dynamics is a behavior-oriented simulation discipline, sensitivity of behavior pattern measures, such as equilibrium level or oscillation amplitude to the model parameters should be evaluated in order to explore the effects of parameter uncertainty on the behavior patterns.

Vensim has the capability to do repeated simulations in which model parameters are changed for each simulation. This can be very helpful in understanding the behavioral boundaries of a model and testing the robustness of model-based policies. To do a sensitivity simulation, a list of parameters must be entered that will be changed in the model. The list of parameters used in this model are presented in later section. Manual sensitivity testing involves changing the value of a constant (or several constants at once) and simulating, then changing the value of the constant again and simulating again, and repeating this action many times to get a spread of output values. Monte Carlo simulation, also known as multivariate sensitivity simulation (MVSS), makes this procedure automatic. Hundreds or even thousands of simulations can be performed, with constants sampled over a range of values, and output stored for later analysis.

Table 5WAPP Projected capacity (MW) and energy demand (TWh)

	2011		2015		2020		2025	
Country	Capacity, MW	Generation, GWh	Capacity, MW	Generation, GWh	Capaci ty, MW	Generation, GWh	Capacity, MW	Generation, GWh
Benin	219	1341	299	1835	420	2576	593	3634
Burkina Faso	178	873	239	1173	345	1694	491	2408
Cote d'Ivoire	968	6005	1247	7731	1652	10244	2142	13284
The Gambia	50	239	94	586	135	847	163	1017
Ghana	1629	11107	2113	14454	2775	18828	3675	24803
Guinea	139	608	287	1563	1044	6873	1122	7626
Guinea Bissau	29	141	38	176	83	385	117	545
Liberia	9	47	230	1446	348	2195	373	2324
Mali	199	1136	366	2226	550	3398	693	4282
Niger	149	849	215	1235	287	1609	370	2039
Nigeria	6376	39102	11225	68830	14983	91873	20000	124393
Senegal	456	2654	629	3744	891	5306	1172	6983
Sierra Leone	38	202	110	587	170	907	217	1157
Togo	170	1042	279	1712	426	2609	600	3680

Estimating Off-Grid Generation

Electricity in the West African countries is generated from both grid and off-grid sources to meet demand. This source categories is presented in Table 6. This is to capture all sources from which electricity is generated in the sub-region, particularly Nigeria. However, it is extremely challenging to project the future of off-grid generation. For these reasons, studies of power systems for developing countries have usually ignored off-grid generation. Thus, given the large contribution of off-grid generation in some West African countries, which is unlikely to disappear entirely within 25 years, ignoring it would seriously compromise the practical value of the study. There is no way a good assessment of emissions from electricity sector would be done without accounting for off-grid generation. Consequently, off-grid generation was included in the model development, to enable the model results to be complete as data becomes available and better refined, though recognizing that there would be the inevitable uncertainty. Nevertheless, estimating current off-grid capacity and generation could be daunting for countries prone to paucity of data. In Nigeria for example, generators of 1 MW or greater must be registered, but there are limited data on actual usage and the capacity of other off-grid generation beyond some local surveys. For the present run, the study by World Bank (2013) was adopted. The study examined the effects of this uncertainty via a sensitivity analysis, asking what the results would be if 2009 off-grid generation was 40 percent less or 40 percent more than the current estimate. This was assume for entire simulation period in the model for the base case, and the same off-grid generation mix over time as described below for each scenario. The resulting emission was then evaluated using this assumption.

Table 6 Source categories of electricity supply in West African Countries

Supply source/category	***Description***
Grid-supply	Generation from the power grid
Off-grid A: Backup	Off-grid generation only when on-grid power is unavailable
Off-grid B: Full-time ≥ 1 MW	Off-grid generation which is used full-time even though there is grid access, with generators greater than or equal to 1 MW (which require government registration)
Off-grid C: Full-time <1 MW	Off-grid generation used full-time even though there is grid access, with generators under 1 MW (not needing government registration)
Off-grid D: No grid access	Generation in rural locations with no grid access

Source: World Bank (2013)

Scenarios

Two scenarios, Base Case and LCD Options, on the WAPP electricity system were analyzed. The Base Case scenario represents continuing with business-as-usual using technologies in the electricity system as they currently are without consideration for efficiency and how they contribute to global warming through emission of GHG into the atmosphere. The LCD Options on the other hand, represents the use of technologies with higher efficiency and low carbon emission to replace generation technologies that have high emitting factors. The model is made up of 7 parameters that are subscripted as listed in Table 7. The high leverage points for policy intervention were identified from this 7 (8) parameters, which were used to conduct sensitivity analysis on the model. The high leverage points include (in green colour): 3. For the reason that there are multiple parameters identified in the model as high leverage points, the multivariate sensitivity simulation (MVSS) or Monte Carlo simulation was a natural choice to make.

Table 7Base Case Parameters in the EP-LCD model

	Fuel type	**Capacity (MW)**	**Capacity factor (Dmnl)**	**Capacity Lifetime (Years)**	**Constructio n time (Years)**	**Emission factor (tCO_2/MWH)**	**Normal Per Capita Electricit y Demand (MWH/P erson)**	**Time to Adjust Capacity (Years)**
Grid Technologies	Oil	1410	0.48	25	3	0.4404	0.146	25
	Gas	4892	0.48	25	3	0.4404		
	Hydropower	3760	0.48	50	10	0		
	Coal	32	0.48	25	8	0.9540		
	Nuclear	0	0	25	10	0		
Grid Renewable Technologies	Solar	0	0	25	2	0		
	Biomass	0	0	25	2	0		
	Wind	0	0	25	2	0		
Off Grid Technologies	Diesel Generators	1695.12						
	Gasoline Generators	2118.9						
	Gas Turbines	423.78						

Sources: World Bank (, 2009, 2013); WAPP (2013);

Results and Analysis

Figure 9 presents the Electricity Planning-Low Carbon Development (EP-LCD) Model for analyzing low carbon emission in West Africa electricity system. Details of the model development including its structure and equations for the runs is given in another article. This section discusses the comparison of the results from running the model at Base Case and LCD Options respectively. The Base Case parameters for the model are presented in Table 6. After model structure was established with model and unit checks, it was further validated using values for the parameters from WAPP. As shown in Figure 10, simulation result for the grid electricity generated shows similar patter with that of an independent projected energy demand for WAPP. Figure 11 presents the cumulative emission from generation of electricity in the WAPP System. Between 2011 and 2012, emission of harmful greenhouse gases to the atmosphere dropped as generation also dropped, but began a steady rise for the simulation period to a value of 6.154 billion tCO_2 in 2060.

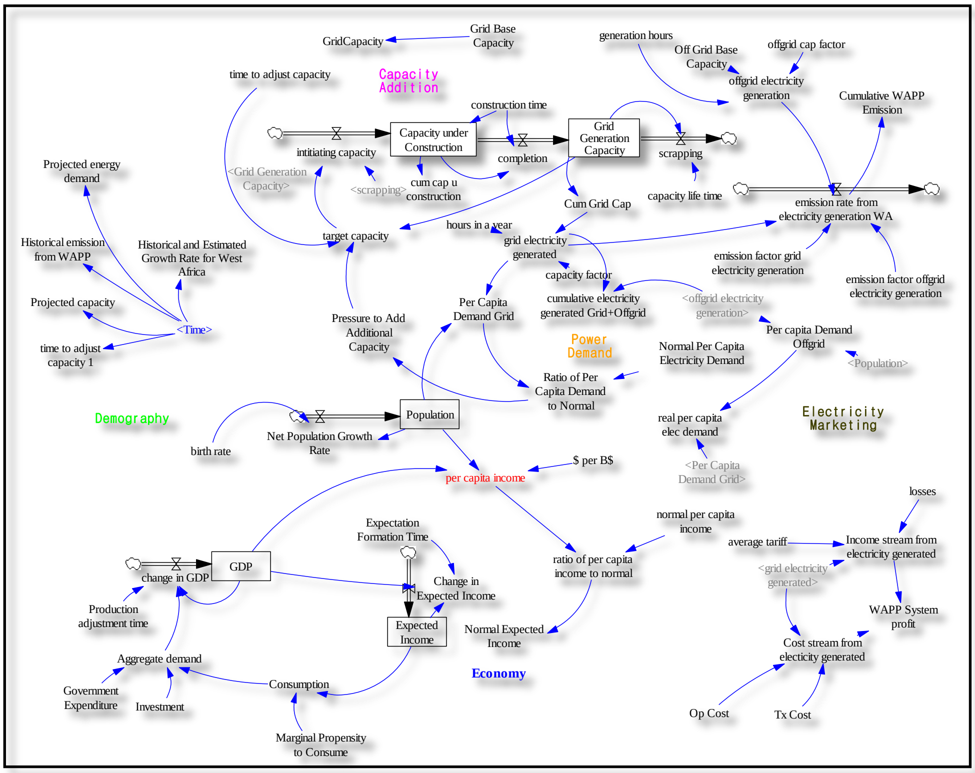

Figure 9 Electricity-Low-Carbon-Development Model

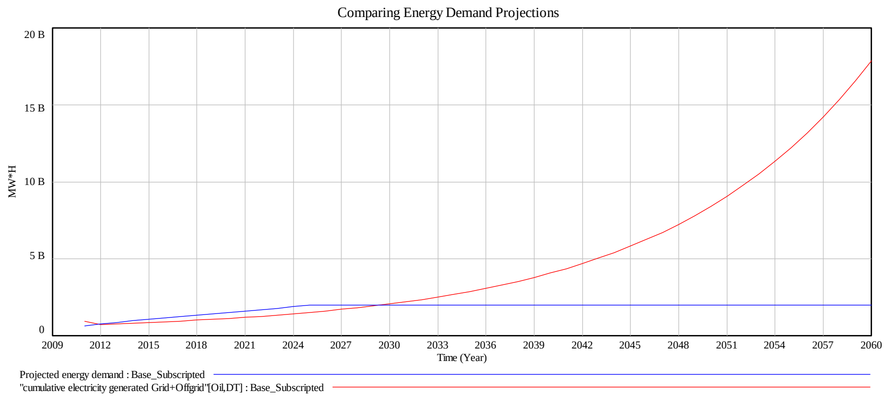

Figure 10 Comparison between projected and simulated generation from grid capacity in WAPP system

Table 8 presents comparative result of cumulative generation capacity, electricity generated as well as emission from the activities in the WAPP system.

Table 8 Cumulative Generation Capacity (MW), Electricity Generated (MWH) and Emission (tCO2)

Time (Year)	2011	2020	2030	2040	2050	2060
Cum Grid Cap, MW	10.1	15.60	38.30	101.90	283.50	807.4
Cumulative electricity generated Grid+Offgrid, GWH	0.66	0.99	2.33	6.07	16.76	47.60
Cumulative Emission-WAPP System, Million tCO2	217.0	333.5	814.0	2,158.2	5,997.4	17,073.1

For the scenario, LCD Options, the parameters used for assessment are presented in Table 9. The values selected were done arbitrarily to test if there would be difference in the outcome of each scenario option. The results indicated that time to adjust capacity is the most significant parameter affecting capacity addition.

Table 9LCD Option Parameters[3] in the EP-LCD model

	Fuel type	Capacity (MW)	Capacity factor (Dmnl)	Capacity Lifetime (Years)	Construction time (Years)	Emission factor (tCO_2/MWH)	Normal Per Capita Electricity Demand (MWH/Person)	Time to Adjust Capacity (Years)
Grid Technologies	Simple Cycle Gas Turbine	1410	0.80	25	3	0.3404	0.546	18
	Combined Cycle Gas Turbine	4892	0.80	25	3	0.3404		
	Hydropower	3760	0.80	50	10	0		
	Coal Subcritical	32	0.80	25	8	0.8540		
	Nuclear	0	0	25	10	0		
	Solar	0	0	25	2	0		
	Biomass	0	0	25	2	0		
	Wind	0	0	25	2	0		
Renewable Grid Technologies	Wind							
	Solar							
	Small Hydro							
Off Grid Technologies	Diesel Generators							
	Gasoline Generators							
	Gas Turbines							

Sources: Dummy values

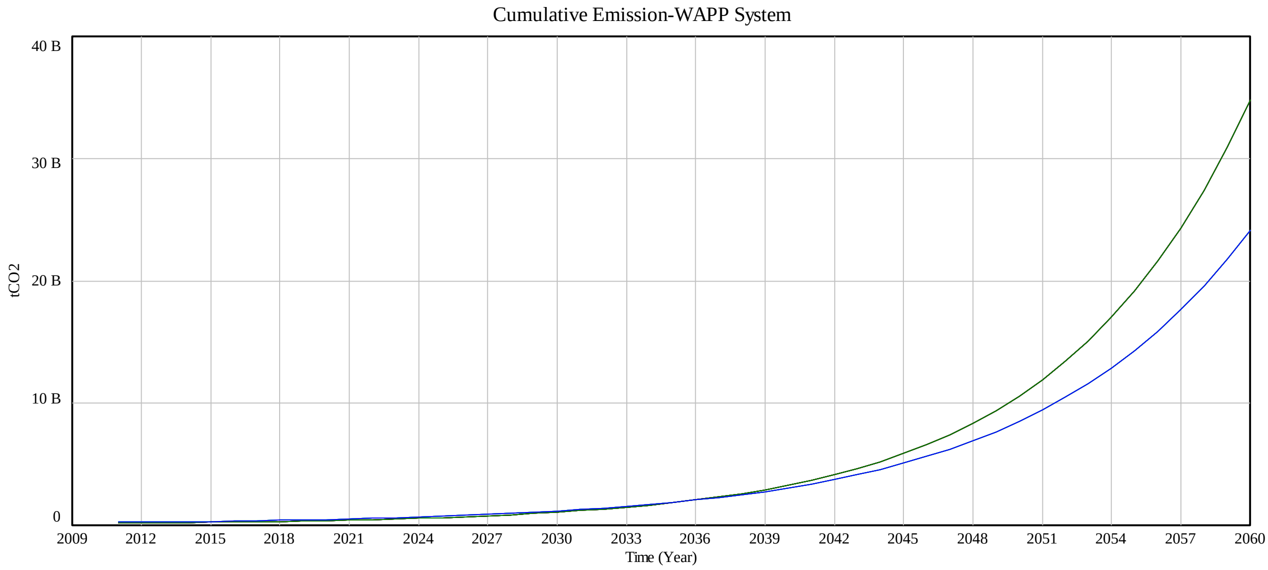

Figure 11 Cumulative emission from electricity generation in WAPP System - Base Case vs LCD Option

Conclusion

The developed model - Electricity Planning-Low Carbon Development - consists of the following sectors/spheres demography, economy, electricity marketing, capacity addition and power demand. For this study, the most critical sector is the capacity addition which includes a sphere for emission assessment from electricity generated in the system. Also incorporated into the model is offgrid[4]-generation to capture how

[3] the values use for this scenario are merely dummy values to compare the outcome to the Base Case in the case of adjustment.

[44] Off-grid generation is got from diesel and gasoline generators as well as gas turbines (World Bank, 2013)

suppressed demand being met in the sub-region. After model structure has been established with model and unit checks done; the model has also been calibrated using values for the parameters identified in the model using data from WAPP and the high leverage points identified. Sensitivity analysis had been conducted to bring out important conclusions and inferences. However, the model development is still work in progress and would need further validation especially concerning the economy sector. Comparing the result of the two scenario runs show that the high leverage points in the model are: capacity factor, adjustment time for capacity and emission factor. The first two are relevant to capacity addition and energy generated while the last one was relevant to emission. These are all interrelated in the model as a system as improving the capacity factor and reducing the adjustment time for capacity leads to lower capacity addition needed with lower emission for the same level of generation.

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