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Optimization of Integrated Energy Systems in a Developing Economy using Clean Non-Renewable Energy (Natural Gas)

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Abstract

This paper attempts to address the perennial energy dearth issue which plagues developing economies, while minimizing associated environmental impact such as Green House Gas, (GHG) Emissions. It uses the Low Emissions Analysis Program (LEAP) model and the Next Energy Modeling System for Optimization (NEMO) component to optimize the integrated energy systems of a developing economy (Nigeria) over 2020 – 2050 modelling period using Clean Non-Renewable Energy (Natural Gas).

The study modeled the developing economy for baseline and Clean Non Renewable Energy (Natural Gas) application and concluded that Clean Non-Renewable energy has a significant impact on the energy capacity and emissions reduction, Energy demand is expected to grow over the modelling period by about 12% and 18% for the Base and Clean Non-Renewable Energy (Natural Gas) scenarios respectively. This indicates that the enhanced use of natural gas results in significant improvement in energy capacity and consequently, ability to supply the needed energy.

Keywords: Developing Economy, Emissions, LEAP, Optimization, Non-Renewable Energy, Sustainable Development

Introduction

The three key factors which define the wealth of nations and economies are Investment, Productivity and Technology. These factors, which ultimately impact level of development, are dependent on the availability of and access to energy. They are measured by the standard of living and income of the populace as well as economic and industrial development rates which are typically above average for developed countries and below average for developing economies. The developed economies typically have very well developed energy sectors and not only provide sufficient energy for their population but continue to expand their capacities to cater for future needs. This is not the case for developing economies which generally struggle with energy dearth.

There are numerous methods available for the optimization of the energy systems. These include theoretical, analytical or modelling approaches. Typically, the modelling approach has been adopted by developed economies with positive results. Unfortunately these models are usually not suitable for application in developing economies particularly due to the unavailability of data required to robustly model the system and get desired results.

This study adopts the modelling approach and uses the LEAP tool with NEMO component for the optimization of the integrated energy system of an example developing country, Nigeria. It focuses on the results obtained from the application of Clean Non-Renewable Energy (Natural Gas) for the optimization effort.

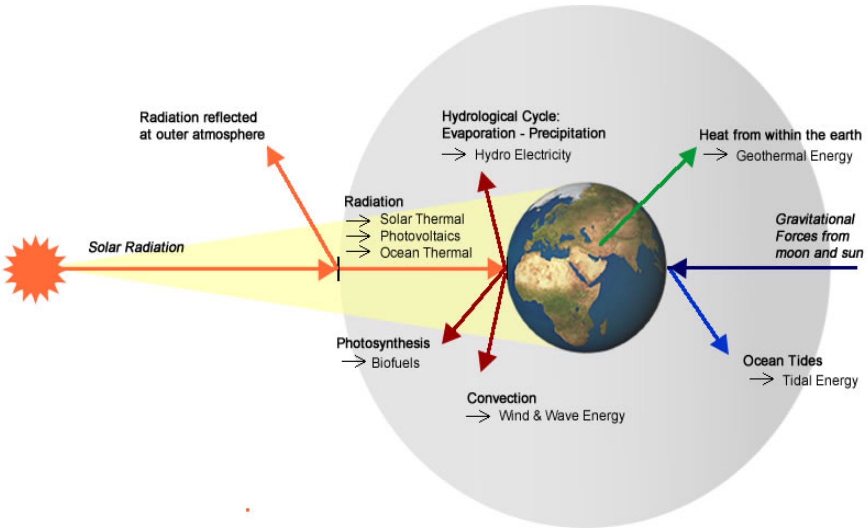
1. Literature review

Energy; Renewable, Non-Renewable Energy & Clean Non Renewable Energy:

Energy is important for man's existence, economic well-being and advancement at individual, organizational, local, national and global levels. Thus the optimization of integrated energy systems to aid efficient provision of affordable energy for people to subsist, commute and execute commercial and industrial activities, is an important subject.

Energy, which is the "ability to do work", is generated using renewable and non-renewable sources. Renewable energy (also called "green energy") is generated from sources that can be replenished naturally faster than they are utilized and hence sustainable as sourced from the Sun (as direct Solar energy or indirectly such as Biomass, Hydro, Wind or Wave), Geothermal and Tidal *(*due to Gravitational forces between the Sun, Moon & Stars) as illustrated below.

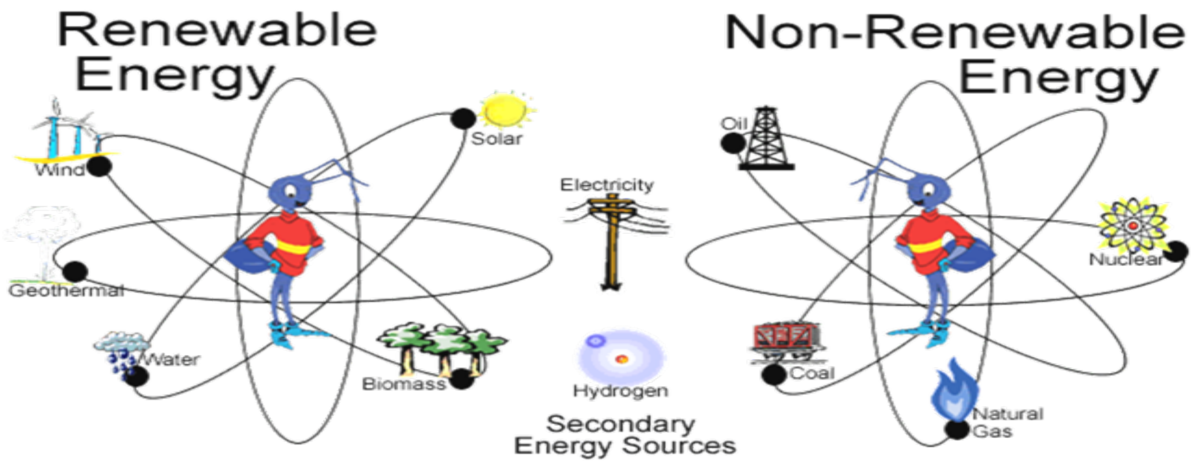
Figure 1: Energy Sources



Energy Economics (Dayo, 2019)

The figure below illustrates Renewable and non-Renewable energy. As illustrated, Non-Renewable Energy includes exhaustible sources of energy which are depleted faster than they can be replenished and include Coal, Crude oil, Nuclear, Natural gas. Of these sources, natural gas has the least environmental (GHG emission) impact and is therefore considered to be clean non-renewable energy.

Figure 2: Renewable and Non Renewable Energy.



Sources: Researchgate.org

Developing Economies:

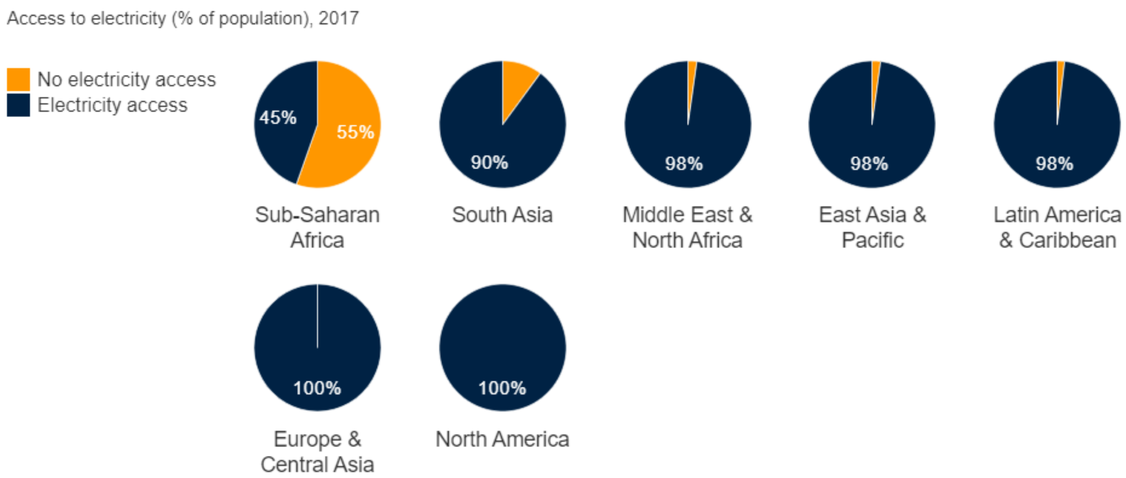
The International Monetary Fund's (IMF) list of developing economies include countries with an aggregated population of over six (6) billion people which represents over 80% of the global population and include Africa, South and Central America, Most Asian countries and some Island nations.

Energy in Developing Economies:

Developing economies do not typically have sufficient energy capacity and struggle with inadequate or aging infrastructures limiting their ability to provide energy for their teeming populations. Addressing this energy dearth is generally acknowledged to be the bedrock for achieving infrastructural development, technological advancement, social stability and well-being and ultimately self-sufficiency.

One of the factors used to categorize developing economies is access to energy as most of such countries suffer from energy dearth and lack of access to energy. The figure below further illustrates this and as indicated, shows developing counties are mostly in Sub-Saharan Africa and South Asia.

Figure 3: Access to electricity in Economies.



World Bank - World Development Indicators, 2017

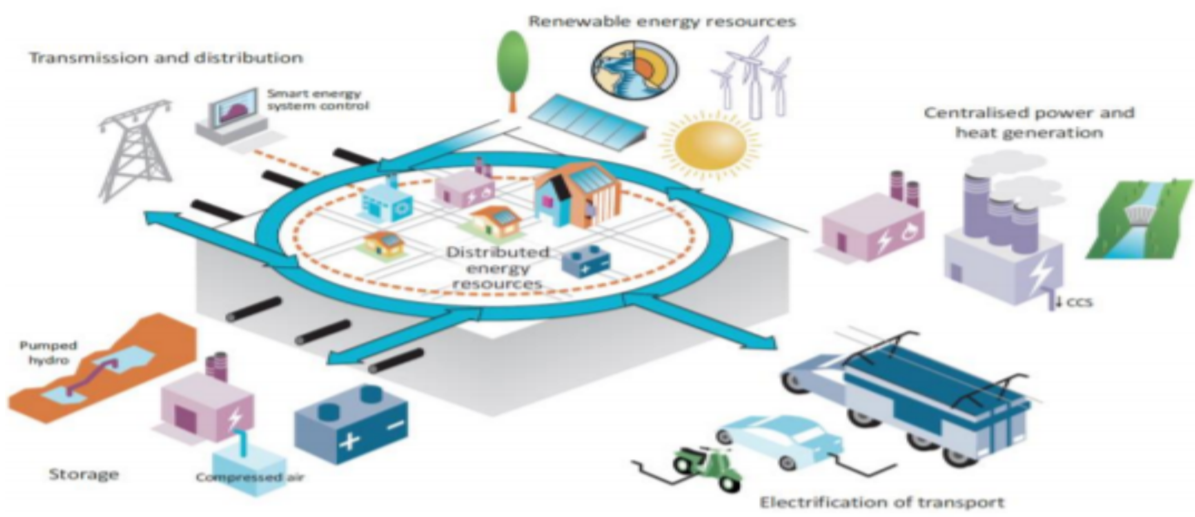
Energy in Developing Economies - The Nigeria Example:

The energy sector of Nigeria continues to struggle with energy dearth despite the investment of significant funds on infrastructural development as allocated funds are typically diverted to other purposes due to corruption. It is estimated that 56% of Nigerians do not have access to electricity, 75% do not have regular access to electricity and 41% of industrial and commercial organizations generate their own electricity (Njoku, 2016). This is attributed to the limited (4,800 - 5,000 MW) electricity generated in the period 2015 / 2016 and similar quantities in recent years. This resulted in skepticism amongst experts over the country's ability to generate 20,000 MW of electricity by 2020 as originally planned and this skepticism was proved to be accurate since Nigeria's electricity generation capacity was estimated to be 12,000 MW by June 2020 with only about 7,000MW available (Enebe & Moveh, 2017). This is so as numerous efforts to restructure the country's energy sector and enhance its efficiency have proved abortive (Ikuobasi et al., 2018).

Integrated Energy Systems:

Integrated energy systems are end to end aggregation of the various sectors, sections and units within the economy. They span generation, transmission, distribution and utilization within the economy and include industrial, commercial and residential consumers within various sectors of the economy (industrial, commercial, Agricultural and Transportation). The system comprises of various energy types including renewable and non-renewable energy sources. They also incorporate efficiency aiding elements such as energy storage, carbon capture and sequestration for emission reduction, and smart grid systems such as single, multiple and micro grid systems where applicable. An example of an integrated energy system is illustrated in the figure below. It lends itself to hub analysis which is an effective and efficient way of analyzing such systems.

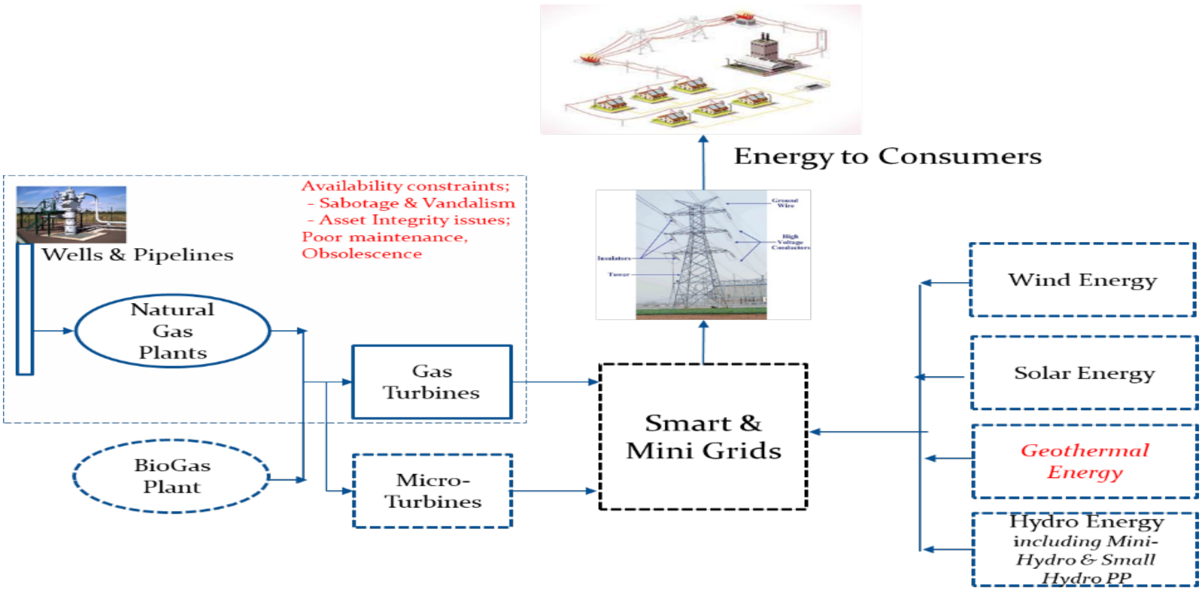
Figure 4: Integrated Energy System – Sector View



Energy Technology Perspectives. IEA, 2014

An additional illustration of the integrated energy system which shows the input energy sources is shown below;

Figure 5: Integrated Energy System – Input Energy Source View



Researchgate.org, Engineersadvice.com, Author

The figure illustrates the peculiar challenges faced by developing economies such as Nigeria. The system leverages the abundant availability of natural gas, a non-renewable albeit relatively clean energy source when compared to coal and crude oil, to optimize the system. It includes, for example bio-gas plants and "small modular sized" power generation plants and other plants applicable to the developing economy in view. This is usually dependent on the socio-economic challenges faced by the economy. It leverages deployment such as the installation of small-sized Micro-Turbines within, or next to, oil and gas facilities to mop up and utilize un-utilized natural gas which would otherwise be flared. It also leverages the concept of decentralization of energy resources using a regional (hub) approach, by utilizing locally available energy sources through pragmatic strategies.

Clean Non-Renewable Energy (Natural Gas) Application in Integrated Energy Systems:

The use of Gas fired Thermal Plants with Turbines installed in the Niger Delta (example of Afam, Omoku, Trans-Amadi, Gbaran, etc.) with the associated significant contribution to energy generation and supply to the Nigerian population offers a viable template for replication consideration. Challenges associated with this structure, which needs to be managed, is the need to transmit the energy generated through the national grid with limited priority assignment especially during periods of high levels in natural water bodies feeding hydroelectric plants which have higher dispatch priority. This challenge is exacerbated by frequent grid collapse resulting from old, sometimes obsolete equipment, vandalization and sabotage. Additional challenges associated with the maintenance, theft and sabotage have typically had significant impact on the availability and reliability of integrated energy systems and therefore need to be effectively managed. These were factored into the model using various factors which can be modified to suit the developing economy in focus.

Conceptual and Theoretical Framework:

Geidl et al. (2007) studied the 'Hub' concept using multiple energy carriers and different energy forms to optimize energy system over a 30 - 50 years' futuristic time horizon focused on three key approaches; transformation, conversion, and storage.

Salimi et al. (2015) progressed the work done by successfully modelling the integrated energy hub and studying the optimization of energy hubs in interconnected energy systems using natural gas and electricity supply planning. Maroufmashat et al. (2015) modelled and optimized an energy hub network with focus on improving economic and environmental emission considerations thus deepening the concept. However, the practical implementation, which was on building systems, limited the applicability as the study was conceptual. Building on previous studies, the International Energy Agency (IEA, 2016) developed sustainable energy supply scenarios in West Africa using the Model for Energy Supply Strategy Alternatives & their General Environmental Impacts (MESSAGE) tool. However, the Demand side management strategy was not implemented in the modelling approach.

Taqvi (2018) further progressed the study of the Energy Hub Concept by applying it to energy systems in Abu-Dhabi. The application was however not extended to integrated energy systems and was not applied in a way suitable for replication in developing economies. Specifically, the work was centered on oil refineries & the transportation industry, but also yielded some opportunities for further studies.

Maroufmashat et al. (2019) modelled and optimized an Energy Hub based energy system through a comprehensive review which deepened the integration options. Sambo (2009) focused on Africa in their study and considered economic growth (GDP) as the only factor influencing energy demand with limited focus on optimization. Emodi et al. (2017) used Long-range Energy Alternative Planning system (LEAP) model to evaluate Policy scenarios for low carbon development in Nigeria and recommended pragmatic energy mix for supplying Nigeria's energy requirements by 2040. Though the study adopted a practical approach, it had a limited focus on energy system performance sustainability.

Onyije (2019) modelled Sustainable Electricity Supply for Nigeria using LEAP Tool and considered GDP & future energy policy factors to demonstrate their impact on demand. The study recommended a framework for sustainability assessment but did not fully consider the impact of consumption efficiency induced by energy policies.

The gaps identified in literature reviewed are summarized as follows;

- Minimal or no application of available clean non-renewable (natural gas) for robust modeling of integrated energy systems.
- Models are more suited for developed economies with typical peculiarities & challenges faced by developing economies, such as huge rural communities, vandalism and sabotage related security issues resulting in availability constraints, neither factored in nor duly accounted for.

This offers an opportunity for the application of more robust framework on modelling and optimization of integrated energy systems in developing economies with appropriate focus on sustainability (low GHG emissions) indices.

The study therefore builds on previous studies and optimizes the integrated energy system of Nigeria as an example of developing economies, using Clean Non-Renewable Energy.

2. Methodological framework

The material used for the study is the LEAP modelling tool with its NEMO compliment.

The method applied was to model the end-to-end integrated energy system covering generation, transmission, distribution and utilization. For generation systems, it models the existing system including Hydro-Electric Dams and Power Plants, Simple / Combined Cycle Gas Turbine / Generator Power Plants. It then models the system for the modelling period of 2020 to 2050 including enhanced natural gas supply from upstream assets aided by optimization and enhanced security and maintenance. For transmission and distribution systems it covers transmission systems with grids and accounts for dispatch strategies and efficiency levels. It also models interruptions and accounts for thefts and losses due to third party activities. For utilization it covers demand from all sectors of the economy (industrial, commercial, agricultural, manufacturing, residential, transportation and others).

Energy demand was computed as a function of population, GDP and sectorial distribution with demand characteristics. Using projected population growth rates, the demand for the modeling period was then computed. Model results include energy demand and environmental impact (Direct and Indirect Green House Gas Emissions) profiles for the extended cycles (up to 100 years) of the economy modelled.

The study builds on previous studies by Onwuka (2018) and Onyije (2019) to optimize the integrated energy system of the developing economy (Nigeria) using Clean Non-Renewable Energy (natural gas). The theoretical basis used by previous authors were optimally combined to achieve the desired modelling approach. The over-arching premise is that the population of the country is a function of the population in the previous year and the population growth rate while the forecasted energy demand for the subsequent year is a function of the energy generation rate and the population. Mathematically, Population Forecast in the year is the product of Population in previous year and Population growth rate as shown in equation (1) below ;

$$P_i = P_{i-1} (1 + P_r) \qquad (1)$$

Also, Energy Demand Forecast is computed as the product of Energy Generation rate per population and Population of the Country as shown in equation (2) below ;

$$ED_i = \{ED_{i-1} * (1 + P_r)\} \qquad (2)$$

This implies that the quantity of energy demanded is proportional to the amount of energy demanded & the population. The Energy Demand Forecasted is therefore estimated from the Energy Demand in the preceding year adjusted to reflect the impact of GDP rate and Optimization using Clean Non-Renewable Energy (Natural Gas) as shown in equation (3) below;

$$EDBOP_i = \{ED_{i-1} * (1 + O_{i-1}) * (1 + GDP_{i-1}) * (1 + P_r)\} \qquad (3)$$

Where

P_i is the forecasted population in year i

P_{i-1} is the previous year's population

ED_i is the energy demand forecast in year i

ED_{i-1} is the energy demand in the previous year

P_r is the population growth rate

O_{i-1} is the Optimization factor (Enhanced system efficiency impact due to Clean Non-Renewable Energy (Natural Gas))

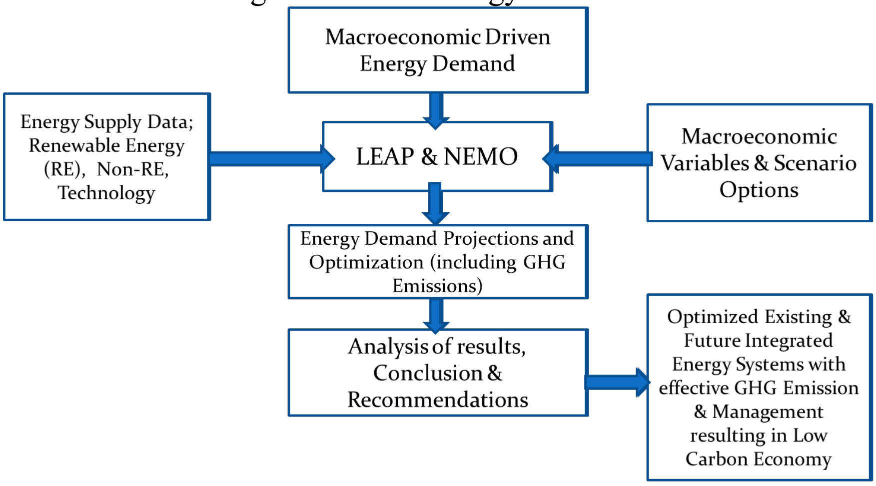
GDP_{i-1} is the GDP growth rate in the previous year

B = Base analysis

BOP = Base with System Optimization using Clean Non-Renewable Energy (Natural Gas)

The methodology adopted for this research work is illustrated in the flowchart below;

Figure 6: Methodology Flowchart



Source: Authors

The modeling and optimization study uses the LEAP and NEMO to evaluate existing and future energy systems of developing economies (Nigeria). It then develops a framework for the model application to other developing economies. The choice of LEAP as the modelling tool was based on its robustness as revealed by the detailed comparatively analytical study of various modeling tools and applications for their suitability for modeling such energy systems conducted by Ringkjob et al (2018). Their study, which focused on seventy five (75) tools and categorized them based on their capabilities for modelling traditional Non-Renewable energy, Renewable Energy, Technology applications, GHG reduction systems and other aspects, confirmed the robustness of the LEAP model for the intended application. Apart from the advantage of using LEAP's 'Freedonia' database to address the data dearth typically experienced in the modelling of developing economies, the newly introduced NEMO program for optimization effectively accounts for rural energy demand. This is a critical requirement for developing economies since rural areas account for a huge proportion of the national population (Bhattecharyya, 2009) making the tool an unrivalled match for the assignment. Conclusively, the robustness of the choice of LEAP the modelling tool of choice for the study. This was confirmed by the fact that major institutions (Natural Resources Defense Council in the United

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States of America, Chinese Energy Institute of China, etc.) and many national economies utilize the tool for their modelling requirements as reported by Heaps (2012).

In order to achieve the modelling objectives, the structure of the integrated energy system of the developing economy was developed while making provision for typical resources which may be applicable to other developing economies in order to ensure easy application of the tool. This was achieved by dis-enabling non applicable aspects using zero parametric assignments for the example economy. Historical Performance data, Capacity (current and future), population, population growth rates, etc. was secured, uploaded into the model and results obtained.

3 Results and Discussion

A snip of the Model Developed with the energy demand result is shown below;

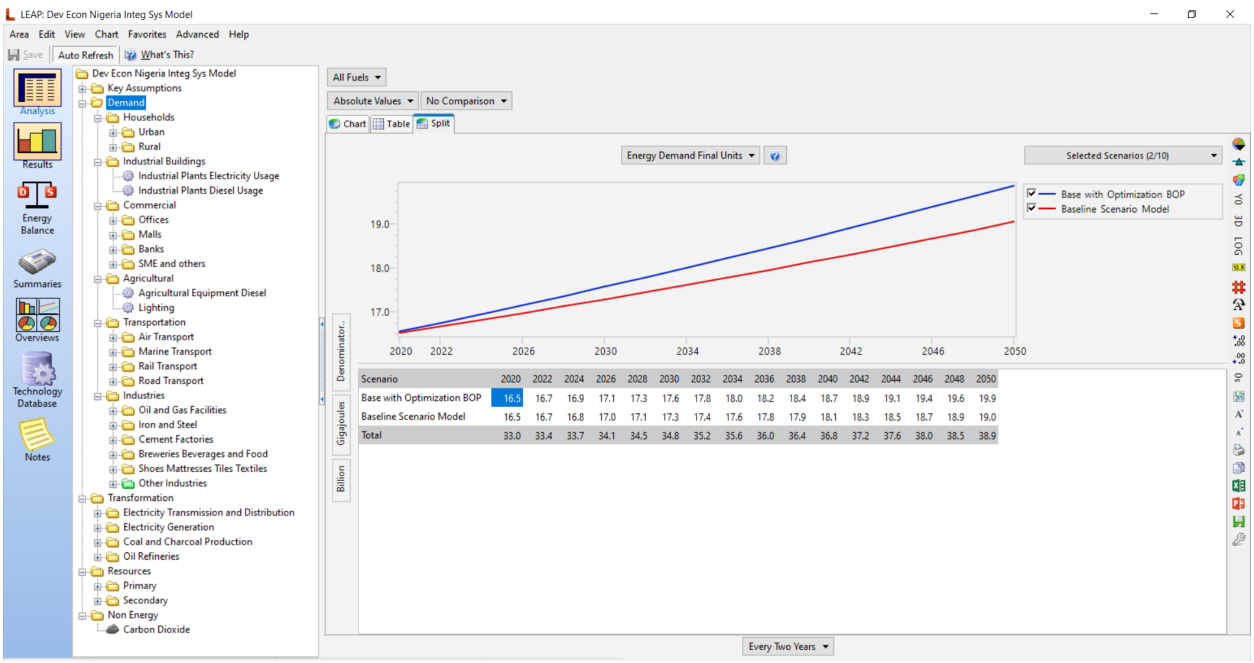
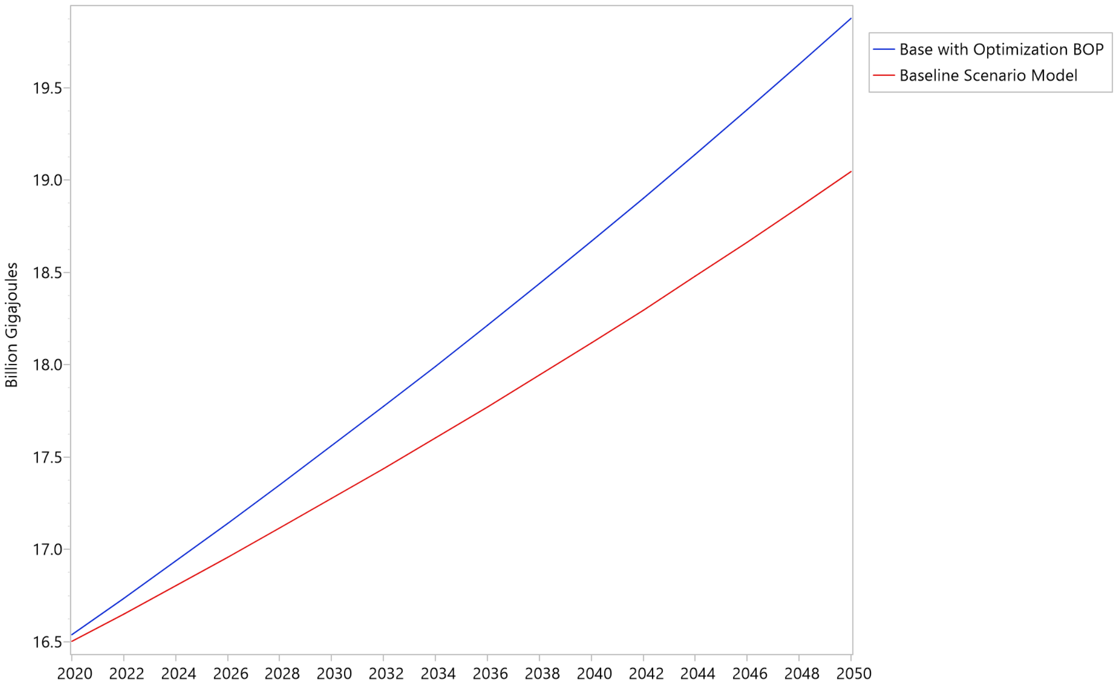


Figure 7: LEAP Model with Energy Demand Results



Source: Authors

It shows the end to end integrated system model on the left panel.

A snip of the Model Developed with the GHG Emissions result is shown below;

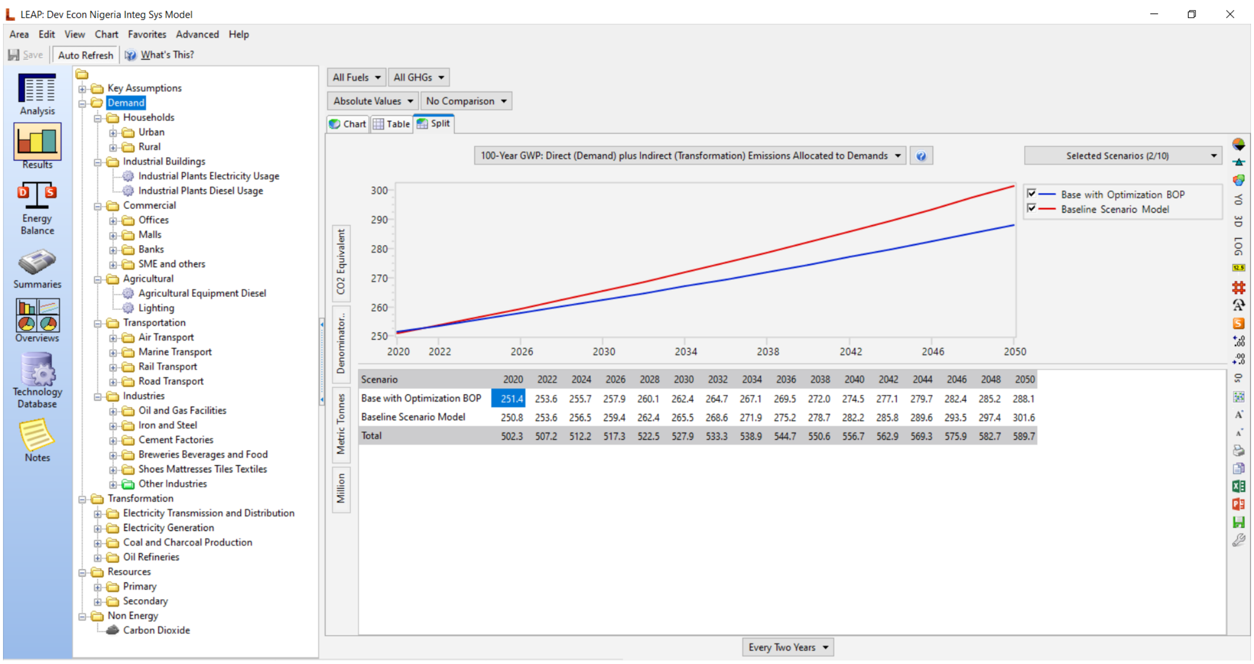


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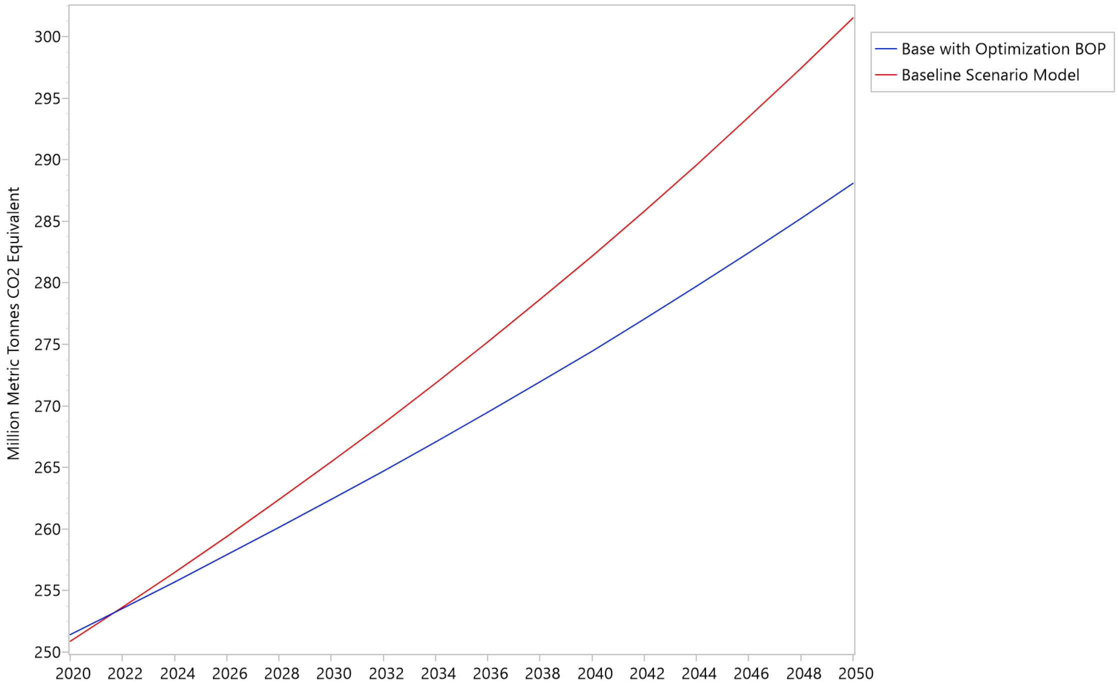
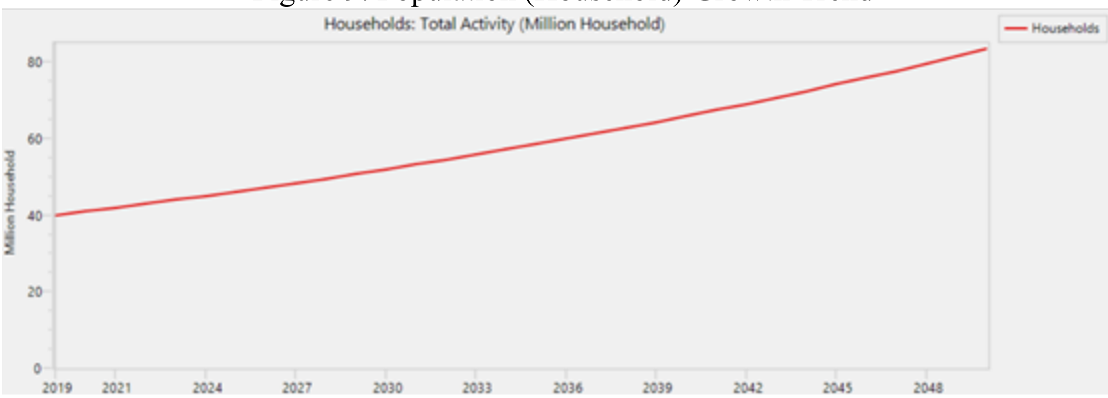
Figure 9: LEAP Model with GHG Emissions Results



Source: Authors

The Population profile for the modelling period of 2020 – 2050 is shown below and is premised on each household having five (5) persons;

Figure 9: Population (Household) Growth Trend



Source: Authors

The analysis of this result indicates increased Energy Demand for the Base scenario and BOP (Clean Non-Renewable Energy (Natural Gas) Scenario) scenario. It indicates that the Base scenario has 15.2% increase in energy consumption over the modeling period of 2020 to 2050. This is significant and represents the 'Do nothing' or 'Maintain status quo' scenario.

This result indicates that the Clean Non-Renewable Energy (Natural Gas) scenario results in 20.6% increase in energy consumption over the modeling period of 2020 to 2050 indicating that the Clean Non-Renewable Energy (Natural Gas) efforts do result in an increase in energy availability and consumption. However, considering the fact that the energy system being optimized to generate more energy is predominantly non-renewable, the associated GHG emission is expected to be higher.

These results obtaained also indicate that the 100 year direct and indirect emissions associated with the Base and Clean Non-Renewable Energy (Natural Gas) Scenarios have increased by 20.3% and 14.6% respectively.

4 Discussion of Findings

The results obtained from the model indicate that energy dearth in developing economies is expected to persist if no strategic action is taken. This is in addition to the worsening environmental impact associated with the continued over-dependence on non-renewable energy. On the backdrop of this, key findings from the results obtained from the modelling exercise are discussed below;

- The population is expected to grow over the modelling period in the modeled scenarios with the Base scenario growing 100%. Population growth is a natural phenomenon which results in increased energy demand. For developing economies where energy dearth exists, it results in worse conditions. Additionally, where the energy source is not clean, increased energy consumption results in increased environmental impact due to increased GHG emissions.
- The Base scenario has 15.2% increase in energy consumption over the modeling period of 2020 to 2050
- This result indicates that the Clean Non-Renewable Energy (Natural Gas) scenario results in 20.6% increase in energy consumption over the modeling period of 2020 to 2050 indicating that the Clean Non-Renewable Energy (Natural Gas) efforts do result in an increase in energy availability and consumption. However, considering the fact that the energy system being optimized to generate more energy is predominantly non-renewable, the associated GHG emission is expected to be higher.
- These results indicate that the 100 year direct and indirect emissions associated with the Base and Clean Non-Renewable Energy (Natural Gas) Scenarios have increased by 20.3% and 14.6% respectively.

- The use of Clean Non-Renewable Energy (Natural Gas) to optimize the integrated energy system, while resulting in increased energy availability, ultimately increases energy demand by about 5%. This impact is within range due to the population increase during the modelling period.

These findings are revealing and significant. Based on findings and analysis for energy demand associated with the application of Clean Non-Renewable Energy (Natural Gas) the following summary are made;

- Energy demand is expected to increase by 15.2% and 20.6% by 2050 (model period) for Base and BOP scenarios respectively.
- Relative to the Base scenario, the BOP scenario results in the marginal increase in energy demand by 0.2% in 2020 & 4.2% by 2050
- With 4.2% reduction in demand relative to the Base scenario over the 2020 – 2050 model period, the optimization of clean non- renewable energy (natural gas) in the energy mix marginally increases energy availability to meet increased demand.

Additionally, based on findings and analysis for emissions associated with the application of Clean Non-Renewable Energy (Natural Gas) the following summary are made;

- Emissions are expected to increase by 20.3% and 14.6% by 2050 (model period) for Base and BOP scenarios respectively.
- Relative to the Base scenario, the BOP scenario results in the marginal increase in emissions by 0.3% in 2020 & 4.6% by 2050
- With a marginal 4.6% increase in demand relative to the Base scenario over the 2020 – 2050 model period, overall there is an increasing environmental impact due to GHG emissions. Implementing Renewable Energy only results in an increase in energy demand.

Conclusion

The detailed analysis carried out used the optimization model developed, which takes into consideration the specific socio-economic challenges plaguing the developing economy (Nigeria) to address underlying constraints impacting system capacity, efficiency and emission reduction.

The implementation of Clean Non-Renewable energy (Natural Gas) into the integrated energy system reveals that it enhances the integrated energy system with positive impact on energy supply, energy consumption and environmental impact (GHG Emissions). Specifically;

- Energy demand is expected to grow over the modelling period by about 12% and 18% for the Base and Clean Non-Renewable Energy (Natural Gas) scenarios respectively. This indicates that the enhanced use of natural gas results in significant improvement in energy capacity and consequently, ability to supply the needed energy.
- The use of Clean Non-Renewable Energy (Natural Gas) to optimize the integrated energy system, while resulting in increased energy availability, ultimately increases energy demand by about 5%. This impact is within range due to the population increase during the modelling period.
- The implementation of Clean Non-Renewable Energy systems is therefore critical for sustainably meeting the energy demands of the future.

Consequently, the following recommendations are made;

- Specifically applicable clean non-renewable energy sources (Natural Gas) should be implemented in the developing country (Nigeria) to address the energy dearth by enhancing supply while keeping the associated GHG emissions low.
- Clean non-renewable energy (natural gas) utilization for the optimization of the integrated energy system should not be implementation in isolation if the positive results on energy demand and GHG emissions required is to be achieved. This is due to the fact that the impact on the environment is still significant though less than other non-renewable energy sources such as coal and crude oil.
- The enhancement of the performance of the integrated energy system requires prioritized implementation of decisive policies. The opportunity to use locally available clean non-renewable energy (natural gas), should be explored. This is in line with the current focus of the government evidenced by the declaration of the decade of gas and would facilitate long term planning, budgeting and funding for other capital intensive energy infrastructure for life cycle effectiveness.
- Structured government intervention through the implementation and sustenance of practical, effective, funded policies should be put in place to create an enabling environment for the target improvement.
- Long term planning, effective and pragmatic measures to address root causes of insecurity which result in sabotage and vandalism of upstream and downstream gas supply / distribution infrastructure should be implemented since they are critical success factors

The LEAP model developed for the example country (Nigeria) is a significant contribution to the scientific community as it facilitates understanding of the impact of the application of non-renewable energy (natural gas) to the optimization of the integrated energy system of a developing economy and can be adapted to model any other developing economy. The implementation of the recommendations made from the analysis would result in better management of the integrated energy systems and ultimately reduce or eliminate the energy dearth currently plaguing these developing economies. This would ultimately translates into a positive impact on the socio economic status of the countries in addition to other positive impacts.

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