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Optimization of Integrated Energy Systems in a Developing Economy using Technology

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Abstract: This study uses a Low Emissions Analysis Program (LEAP) model to optimize the integrated energy systems of a developing economy (Nigeria) over 2020 - 2050 modelling period using Technology. It attempts to address the perennial energy dearth challenge, which plagues developing economies, while minimizing associated environmental impact GHG Emissions. The study models existing conditions within the developing economy as a baseline and evaluates a technology application scenario. The results obtained indicate that the application of technology has a significant impact with as much as 70.6% reduction in energy demand and 64.8% reduction in GHG emissions within the modelling period. The application of technology is therefore critical for sustainably meeting the future energy demands of the developing economy modelled (Nigeria). The study recommends that specifically applicable technology identified should be implemented in the developing country to address the energy dearth by enhancing supply while keeping the associated Green House Gas (GHG) emissions low.

Keywords: Developing Economy, Energy, Emissions, Green House Gas, LEAP, Model, Optimization, Sustainable Development, Technology

Introduction

Three key factors which contribute to the creation of wealth for 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 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 systems and get desired results.

This study adopts the modelling approach and uses the Low Emissions Analysis Platform (LEAP) tool with Next Energy Modeling System for Optimization (NEMO) for the optimization of the integrated energy system of an example developing country (Nigeria). It focuses on the results obtained from the application of Technology for the optimization effort.

Background and Literature Review

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 and utilization 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. Regardless of the energy source, the application of technology can be used to enhance integrated energy systems. Apart from the use of more efficient equipment to reduce energy consumption

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thus reducing energy dearth and positively impacting the integrated energy system, the application of smart grid systems offers an opportunity for efficient transmission and distribution of energy by reducing losses.

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. It is pictorially illustrated in Fig. 1 and industrial development remain below average.

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 sufficient energy for their teeming populations. Addressing this energy dearth is generally acknowledged to be the foundation for achieving technological advancement, infrastructural development, social stability and well-being ultimately resulting in self-sufficiency and long term sustainability.

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. Figure 2 further illustrates this and as indicated, shows that developing counties are mostly in Sub-Saharan Africa and South Asia.

Energy in Developing Economies - The Nigeria Example.

The energy sector of Nigeria continues to struggle with energy dearth despite the investment of significant funds in infrastructural development since the funds ended up being diverted to other use and exacerbated by 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 (AV and Nasir, 2017). This is so as numerous efforts to restructure the country's energy sector and enhance its efficiency have proved abortive..

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 Fig. 3.

An additional illustration of the integrated energy system which shows the input energy sources is shown in Fig. 4.

The figure illustrates the peculiar challenges faced by developing economies such as Nigeria. The system leverages applicable technology such as smart grid systems, use of distributed grid systems and off-grid arrangements, where required (typically rural areas), etc. to achieve the optimization objective. Another example is the installation of small-sized Micro-Turbines within, or next to, oil and gas facilities to mop up and utilize un-utilized gas to generate and supply energy to local consumers using mini or off-grid systems (Tan *et al*., 2013). The study also leverages the concept of decentralization of energy resources using a regional (hub) approach, by utilizing locally available energy sources through pragmatic strategies.

A key challenge associated with the integrated energy system, which needs to be managed, is the need to transmit the energy generated through grid systems with associated inefficiencies and losses. For example, in Nigeria, the aged transmission and distribution systems coupled with obsolete equipment, sabotage/vandalism of equipment and frequent grid collapse mount undesirable pressure on the system further contributing to the energy dearth.

Technology Application in Integrated Energy Systems

The application of technology for the optimization of Integrated Energy Systems entails the use of available and applicable technologies either for the direct generation, transmission and distribution of energy or for the reduction of energy consumption especially as technology continues to advance. European Commission conducted studies on the subject and detailed typically applicable technologies. A particularly important feature of technology application to integrated energy systems is the use of energy saving/enhancing equipment since they contribute significantly to solving the energy dearth issue in developing economies by reducing energy consumption using energy efficient techniques. Examples include energy efficiency electricity bulbs such as Light Emitting Diodes (LED), energy efficient air

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conditioners, electric irons, washing machines, dryers, pumps and other appliances that are designed to utilize up to 70% less energy when compared to other units of similar capacities. European economies particularly leverage this opportunity in the European Union's drive towards Zero Carbon Economies. It features as a key contributor with the potential for reducing energy demand by as much as 20%.

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 and 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.

Taqvi (2019) 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 (2009a,b) focused on Africa in their study and considered economic growth (Gross Domestic Product, GDP) as the only factor influencing energy demand with limited focus on optimization. used Low Emissions Analysis Platform (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 and 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 literature review conducted identified minimal or no application of specifically applicable technology in previous work done.

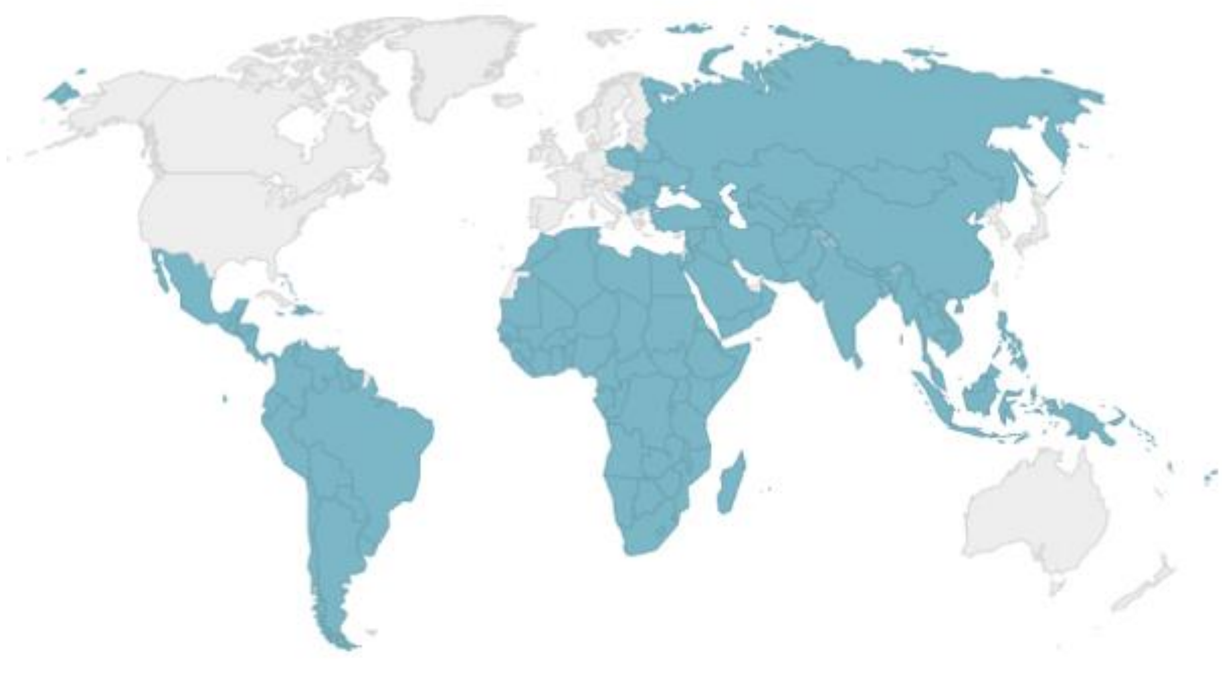

Fig. 1: Map of developing countries (IMF WB, 2017)

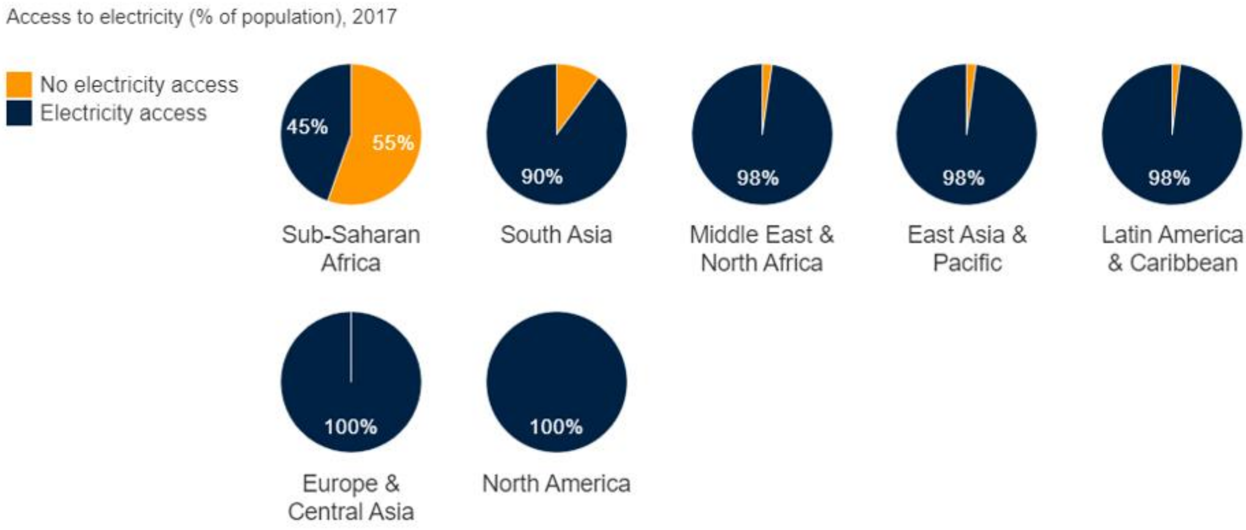

Fig. 2: Access to electricity in Economies. (WB, 2017)

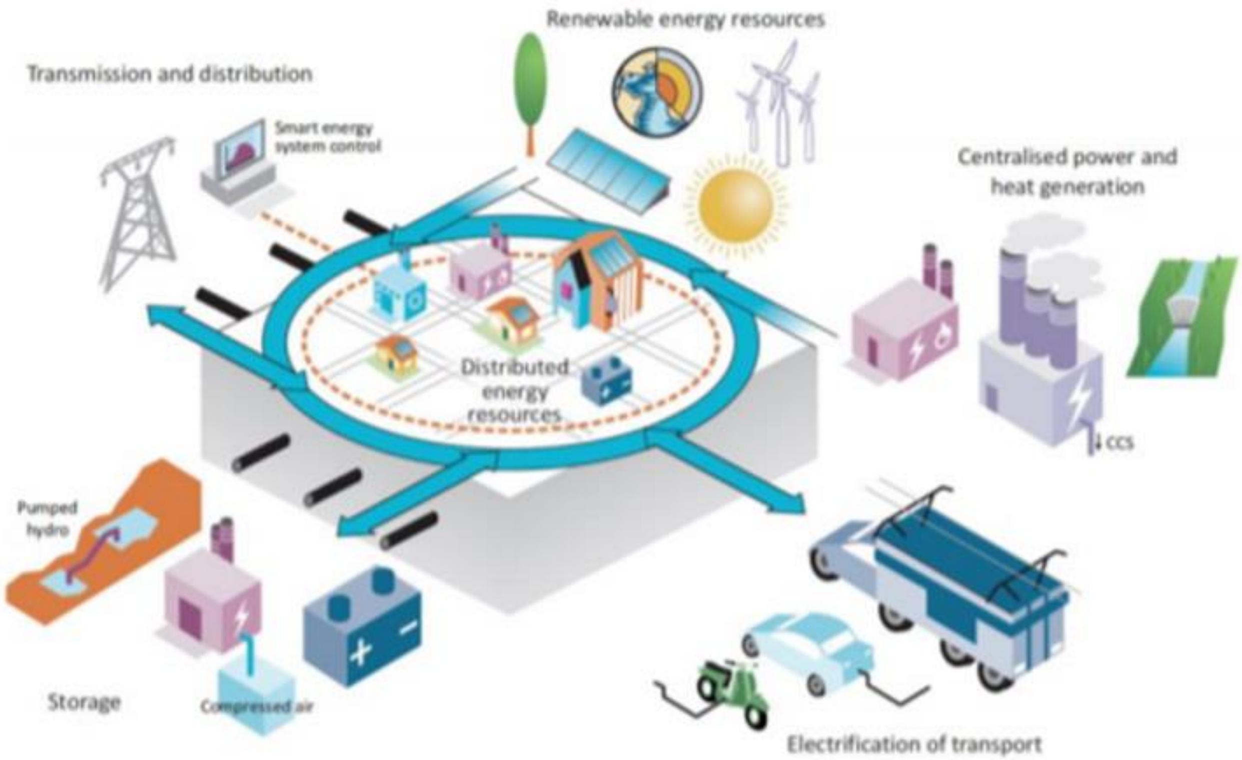

Fig. 3: Integrated energy system – sector view (IEA, 2014)

The models were also found to be more suited for developed economies as typical peculiarities and challenges faced by developing economies, such as huge rural communities, vandalism and sabotage related security issues resulting in availability constraints, were 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 Technology.

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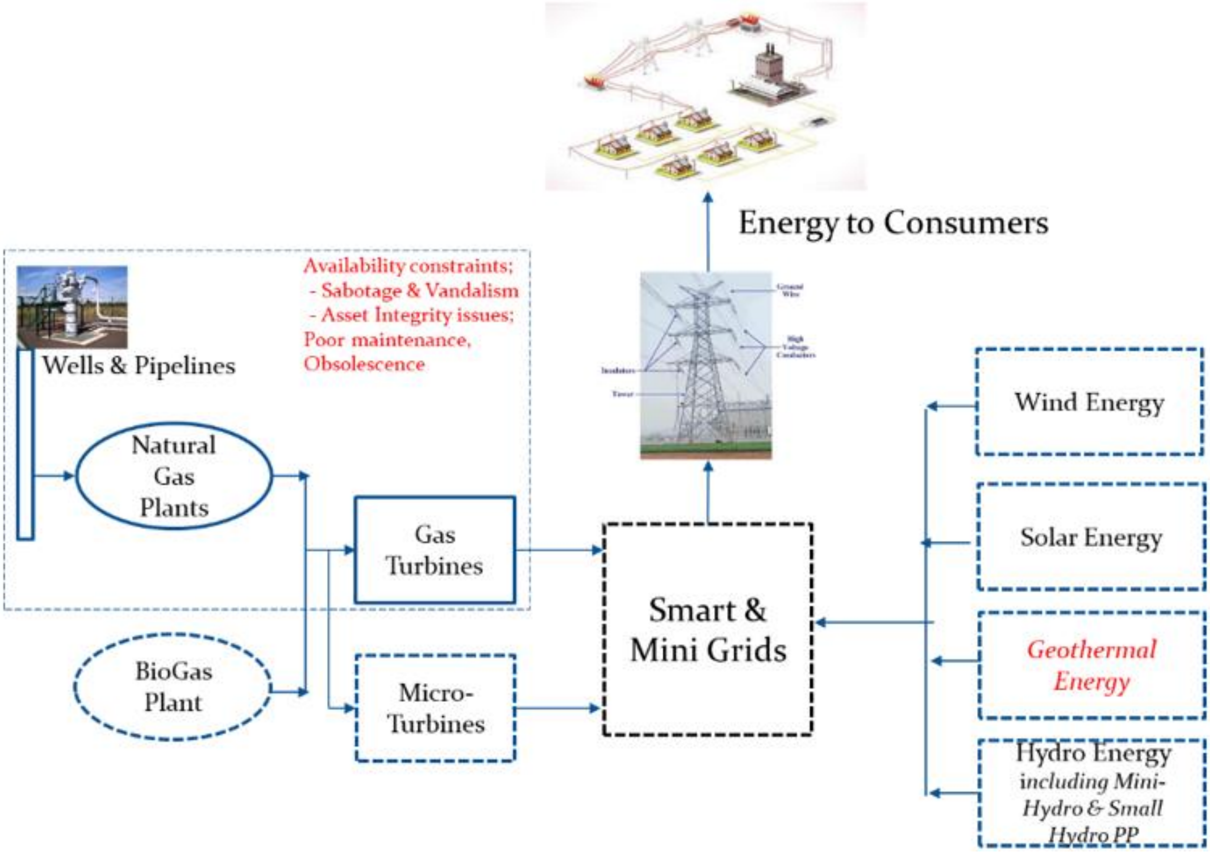

Fig. 4: Integrated Energy System – Input Energy Source View (Researchgate.org, Engineersadvice.com, Author)

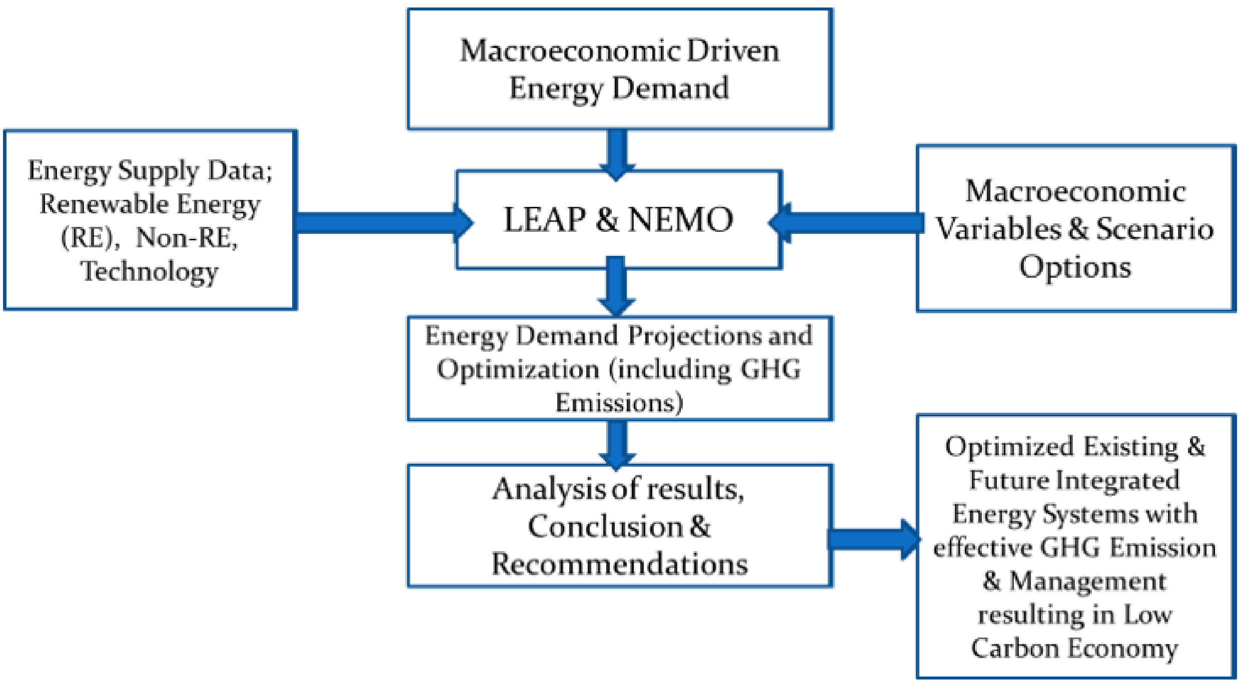

Fig. 5: Methodology flow chart

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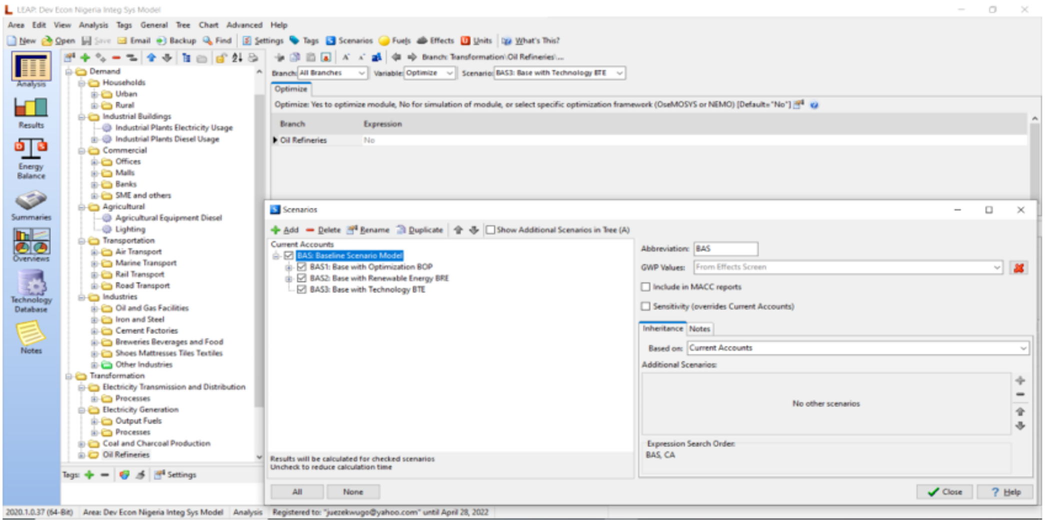

Fig. 6: LEAP model

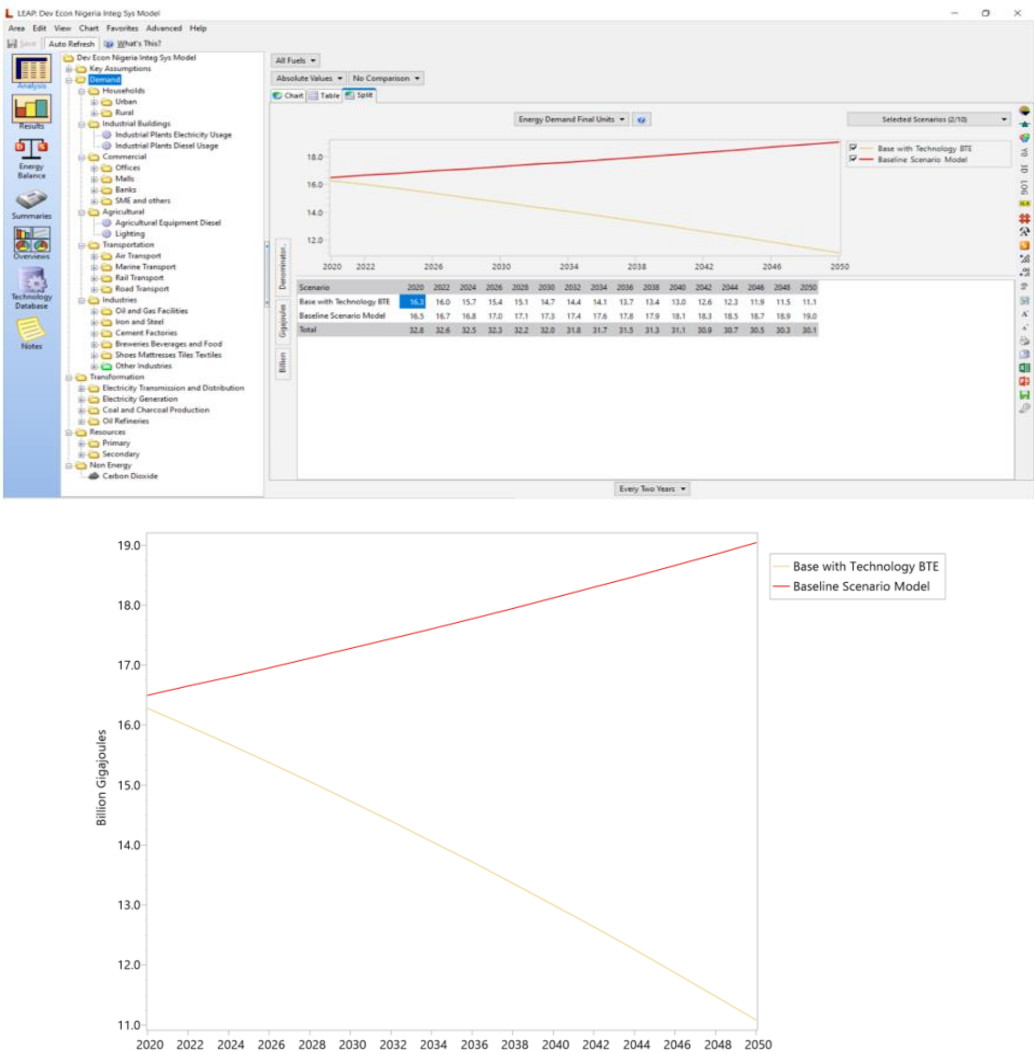

Fig. 7: LEAP model – energy demand

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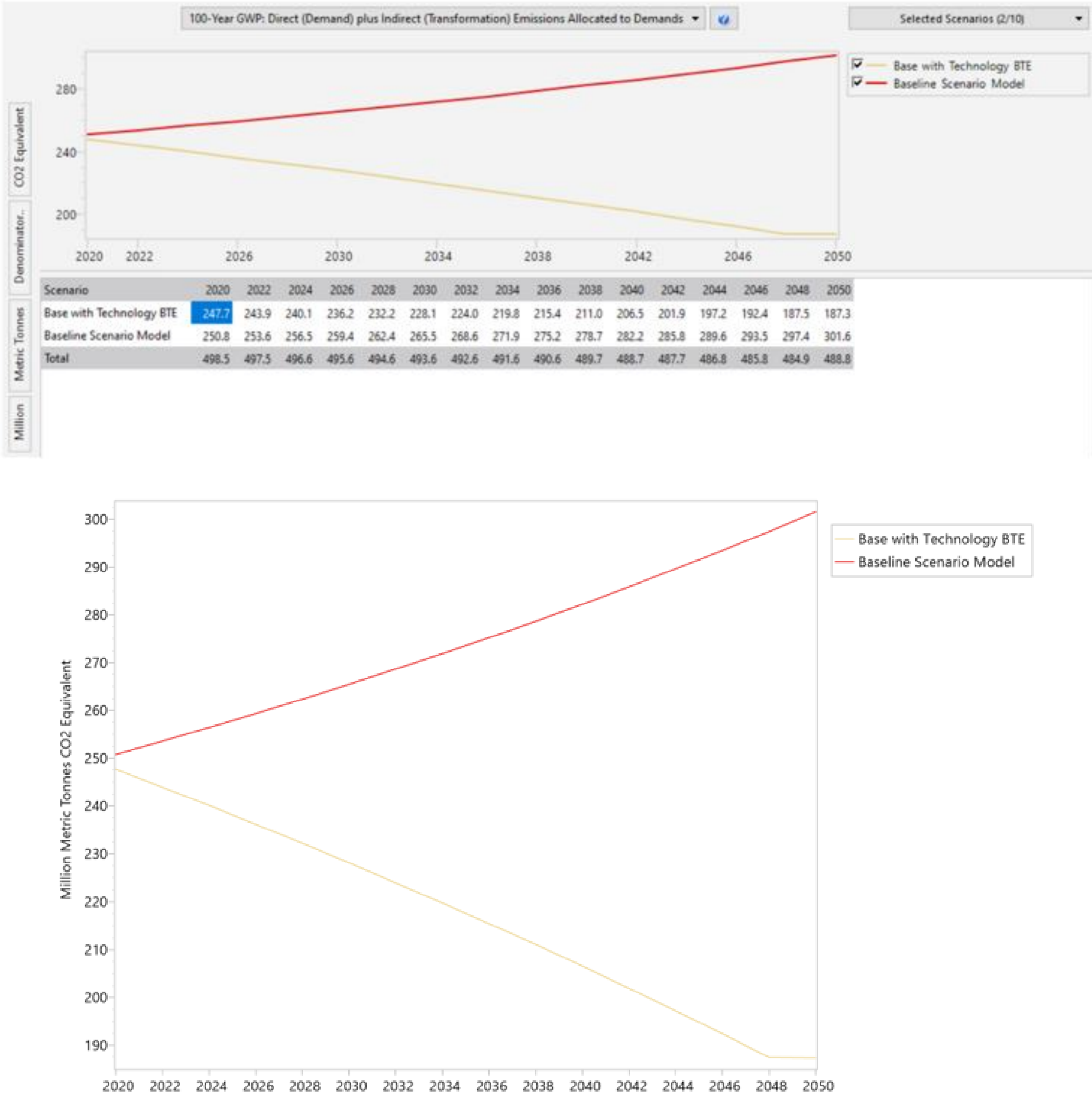

Scenario	2020	2022	2024	2026	2028	2030	2032	2034	2036	2038	2040	2042	2044	2046	2048	2050
Base with Technology BTE	247.7	243.9	240.1	236.2	232.2	228.1	224.0	219.8	215.4	211.0	206.5	201.9	197.2	192.4	187.5	187.3
Baseline Scenario Model	250.8	253.6	256.5	259.4	262.4	265.5	268.6	271.9	275.2	278.7	282.2	285.8	289.6	293.5	297.4	301.6
Total	498.5	497.5	496.6	495.6	494.6	493.6	492.6	491.6	490.6	489.7	488.7	487.7	486.8	485.8	484.9	488.8

Fig. 8: LEAP model - GHG emissions

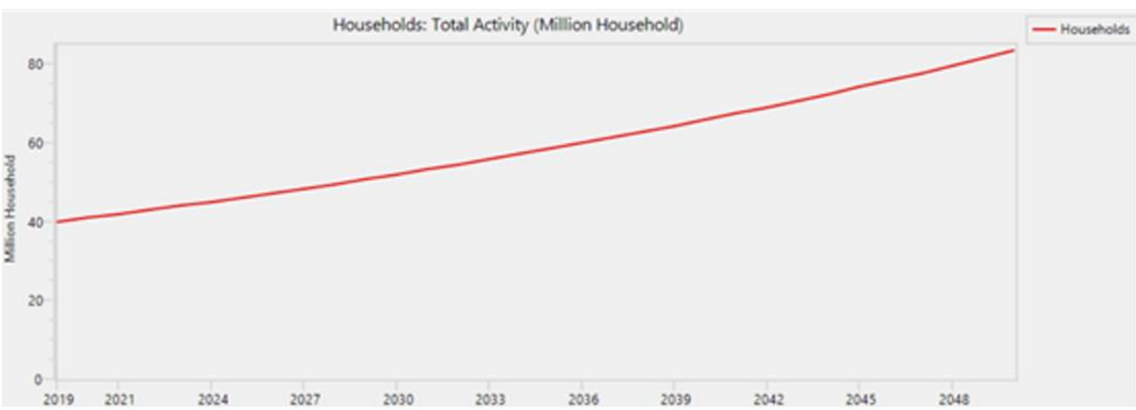

Fig. 9: Population (Household) growth trend

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Methodology

The material used for the study is the LEAP modelling tool with NEMO. 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 period 2020 to 2050 including Technology Sources (Energy efficient systems, Smart Grids, Mini Grids, etc.). 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 to optimize the integrated energy system of Nigeria as an example of developing economies, using Technology by leveraging previous work by Onwuka (2018) and Onyije (2019). The theoretical basis for the analysis is that the population of an economy 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 year is the product of Population in previous year and the Population growth rate as shown in Eq. (1):

$$P_i = P_{i-1}\left(1 + P_r\right) \tag{1}$$

Energy Demand Forecast is computed as the product of Energy Generation rate per population and the Population of the Country as shown in Eq. (2):

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

This implies that the quantity of energy demanded is proportional to the amount of energy demanded and 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 Technology. This is shown in Eq. (3):

$$EDBTE_i = \left\{ED_{i-1} * \left(1 + T_{i-1} - t_{i-1}\right) * \left(1 + GDP_{i-1}\right) * \left(1 + P_r\right)\right\} \tag{3}$$

where:

P_i = The forecasted population in year i
P_{i-1} = The previous year's population
ED_i = The energy demand forecast in year i
ED_{i-1} = The energy demand in the previous year
P_r = The population growth rate
T_{i-1} = The Technology application incremental factor (Smart grids, micro-turbines, etc.)
t_{i-1} = The Enhanced system efficiency (reduction in energy consumption due to more efficient equipment
GDP_{i-1} = The GDP growth rate in the previous year
B = The Base Scenario
BTE = The Base Scenario with Technology application

The methodology adopted for this research work is illustrated in the flowchart shown in Fig. 5.

The modeling and optimization study uses LEAP and NEMO to evaluate existing and future energy systems of developing economies using Nigeria as an example. 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 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 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 example 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.

Results

A snip of the Model Developed, which shows the end to end integrated system model on the left panel, is shown in Fig. 6.

A snip of the Model Developed with the energy demand is shown in Fig. 7.

A snip of the Model Developed with the 100 year direct and indirect GHG emissions result is shown in Fig. 8.

The Population profile for the modelling period of 2020 – 2050 is shown in Fig. 9 and is premised on each household having five (5) persons.

This result indicates that the Base scenario has about 15% 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.

For the Technology scenario, the result obtained indicates that though the Energy Demand for the Base scenario increased over the modelling period, it resulted in a huge reduction in energy demand and associated GHG emissions. The BTE scenario has about 32% decrease in energy consumption over the modeling period. This is a significant reduction achieved through the application of technology to manage energy utilization, with an overall positive impact on the environment.

This result indicates that the direct and indirect emissions associated with technology reduces over the 30-year modelling period. This is significant considering the fact that the Base Scenario has about 14% increase as it shows the huge positive impact of Technology application.

Discussion of Findings

The results obtained from the base scenario of 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. In summary:

- The population is expected to grow over the modelling period in all 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
- The application of technology has a very significant impact on reduction of energy demand with as much as 40% impact. This impact is huge with a potential positive impact on the environment especially in consideration of the fact that the increase is despite increasing populations. The application of technology therefore enhances the sustainability of the energy system over time

These findings are revealing and significant. Additionally:

- Energy demand is expected to increase by 15.2 and 31.9% by 2050 (model period) for Base and BTE scenarios respectively. Relative to the Base scenario, the BTE scenario results in the reduction in energy demand by 1.3% in 2020 and 70.6% by 2050
- With 70. 6% reduction in demand relative to the Base scenario over the 2020-2050 model period, the implementation of Technology results in a huge reduction in energy demand and consequently a very significant impact
- Emissions are also expected to increase by 21.3 and 25.8% by 2050 (model period) for Base and BTE scenarios respectively. Relative to the Base scenario, the BTE scenario results in the marginal decrease in emissions by 1.3% in 2020 and 64.8% by 2050
- With 64.8% reduction in emissions relative to the Base scenario over the 2020-2050 model period, overall there is a significant reduction in environmental impact due to GHG emissions
- The application of Technology in the energy mix results in a significant reduction in energy demand and environmental impact. Consequently, it has a positive impact on the integrated energy system

Conclusion

The detailed analysis carried out used the LEAP 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 application of technology into the integrated energy system reveals that energy sources and technologies modelled are viable within the peculiar circumstances of the developing economy. It enhances the integrated energy system with positive impact on energy supply, energy consumption and environmental impact (GHG Emissions). Specifically

- Technology has a very significant impact on the energy capacity and emissions reduction since it significantly increases energy availability while reducing energy demand by 70.6% and reducing GHG emissions by 64.8% over the 2020 – 2050 modelling period
- The application of technology is therefore critical for sustainably meeting the energy demands of the

future as it has a very positive impact on energy demand and emissions reduction of the developing economy modelled

Consequently, the following recommendations are made:

- Specifically, applicable technology should be implemented in the developing country (Nigeria) to address the energy dearth by enhancing supply while keeping the associated GHG emissions low
- The implementation of the recommended measures should preferably start with simple less capital intensive aspects and then progress to more capital intensive ones; energy saving equipment deployment, optimization of existing systems, implementation of mini-grid systems and SMART Grid systems, etc
- The enhancement of the performance of the integrated energy system requires prioritized implementation of decisive policies. The opportunity to enhance existing and future facilities to increase energy availability by reducing consumption in the short term and long run should be explored. This would facilitate long term planning, budgeting and funding of other capital intensive infrastructure required 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, maintenance and budgetary provisions for the management of the integrated energy system and capital investments in the replacement of existing aging facilities and application of technology are critical success factors that should be enhanced

The LEAP model developed for the example country (Nigeria) is a significant contribution to the scientific community as it has enabled us understand the impact of the application of technology 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 the reduction and ultimate elimination of the energy dearth currently plaguing these developing economies. This ultimately translates into a positive impact on the economy of the countries in addition to other positive developmental impacts.

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Author's Contributions

All authors equally contributed in this study.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

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