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Integrated Assessment Modelling of Energy Transition Pathways for the Nigerian Economy

John, M.P U.[1], Nwaozuzu, C.[2], Nteegah, A.[3]

[1,2,3]Emerald Energy Institute, University of Port Harcourt

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Abstract: The worldwide push for shifting from fossil fuels to renewable energy sources has gained momentum due to concerns about greenhouse gas emissions and their detrimental effects on the environment. Nevertheless, since their discovery in 1958, fossil fuels have played a crucial role in Nigeria's economy, generating substantial revenue and foreign exchange. Any efforts to transition should be grounded in policy frameworks that take into account Nigeria's strengths, weaknesses, opportunities, and potential challenges.

Numerous attempts have been made to create decarbonisation models for Nigeria, each varying in sector grouping, system components, modelling approaches, and pathways. The future evolution of the energy system is challenging to forecast due to multiple variables, including technological advancements, policy changes, socioeconomic factors, financial considerations, and geopolitical influences. A comprehensive assessment model was developed using the pymedeas modelling framework, incorporating Nigerian socioeconomics, energy, climate, land use, water resources, minerals, and transportation systems.

The economic model was built using Nigeria Input-Output Tables (IOT) and its Leontief Matrix covering 1995 – 2014. Simulated GDP was calibrated by historical GDP performance before using the model for prediction. The model was used to assess the impact of renewable Net-zero (NZP), non-renewable (Business-As-Usual (BAU)) pathways, and gas as a transition fuel on Nigeria's socioeconomic growth using Root Mean Square Deviation (RMSD).

GDP growth for NZP was observed to be slow at -3% in the early years compared to an increase of about 2% in the BAU. It peaks up and outpaces BAU from 2038 onward. Nigeria should pursue a policy that allows for aggressive development of its gas resources as a transition fossil fuel, balanced by early and structured investment in centralised renewable energy infrastructures.

Work provides complimentary approach to existing body of literature on Shared Socioeconomic Pathways (SSP). Pymedeas_ng can be used further to explore alternative pathways for decarbonisation of the Nigerian economy. Model modularity in terms of structure and functions means detailed investigation could be done by the user on a range of energy transition subjects.

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I. INTRODUCTION

The gradual shift from fossil to less carbon-intensive energy sources has been termed the Energy Transition. Energy transition has become so popular that fossil fuels are now mentioned in energy discussions as vanquished while renewables are seen as the victor, no thanks to the greenhouse emission that accompanies fossil fuel use. According to IRENA (2024), the energy transition involves shifting the global energy industry from fossil fuel-based sources to zero-emission alternatives by 2050. This transformation aims to reshape the entire energy sector worldwide. This transition encompasses extensive, long-term changes in energy systems, as noted by Davidson (2014) and Geels (2010).

The previous energy transition led to a system reliant on geographically concentrated resources. This concentration enabled certain countries to wield geopolitical influence through resource distribution, resulting in economic benefits for resource-extracting nations. However, we are now shifting from an energy system characterised by scarcity to one with potential abundance for most countries worldwide. This change occurs because the new energy system will offer some degree of energy independence to almost every country, as most will be able to utilise renewable energy sources. But before then, it is the significant matter of getting there.

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With the growing realisation of the impact of greenhouse gases—mainly stemming from fossil fuels—on the environment, along with recent findings from the global scientific community, there is a worldwide push for a shift toward more sustainable energy sources, primarily renewables, that generate minimal or negligible amounts of greenhouse gases. Since 2009, there has been a consistent rise in the proportion of energy derived from renewable sources.

Greenhouse gases encompass water vapour (H2O), carbon dioxide (CO2), methane (CH4), nitrous oxide (N2), and ozone (O3). These gases mainly arise from the consumption of fossil fuels. According to the Environmental and Energy Study Institute (2018), in 2017, fossil fuels accounted for approximately 77% of the greenhouse gas emissions in the U.S, as an example.

As the world population continues to grow and the world economy continues to grow, more and more people require energy to meet their wants, be it for transportation, industrial processes, household, etc. Energy demand has, therefore, been growing due mainly to economic and population growth. Previously, man's resources for satisfying these needs mainly consisted of fossil fuels. The price of fossil fuels has gone through several cycles of boom and bust, obeying the law of demand and supply, and is affected by the oligopolistic influence of OPEC. However, social factors, while unpredictable, and in responding to the negative externalities that scientists have called greenhouse gases and effects, are gradually influencing not only the demand for fossil fuel but also the capital stock that is required to transform fossil resources into energy. Renewable resources, seen as a cleaner form of energy, create a competitive demand for renewable energy resources. Land use will become an essential factor, and energy infrastructure that will make the conversion, transportation, and storage of renewable-based energy available will be key. To ensure energy security for sovereign nations as well as contribute to the protection of the natural environment, sovereign nations, both net exporters and net importers of crude oil, must respond to the impact the shift in the demand and supply curve of fossil will have on their socioeconomic growth. There is a strong need for policymakers to be evident in their approach to avoid the issue of stranded assets and capacity, a significant problem with low carbon transition, but at the same time address the issue of sustainability (Löffler et al., 2019).

Energy transition has come to stay, and with several advocacy campaigns for a more sustainable approach to energy consumption, fossil fuels, which are Nigeria's primary source of foreign earnings, will continue to face stiff competition from renewable energy sources. Although the dual energy challenge is still very much with us, as can be seen from the growth in energy consumption, even for oil, for most emerging economies, investment in the primary energy sector continues to face stiff competition from investment in renewables as investors from advanced economies that are signatory to Paris agreement seek to invest in more sustainable energy companies. Countries like Nigeria, which are also signatories and receive their significant earnings from the non-renewables, will have to be very strategic in their energy policies to ensure balanced, sustainable growth where energy transition policies around the world are not slowing down economic growth and poverty alleviation in the face of a growing population.

This work is aimed at assessing the impact of energy transition pathways on the Nigeria socioeconomic growth. Two key scenarios are analysed namely - renewable energy pathway as known as the Net-Zero Pathway (NZP) and the Non-renewable energy pathway also known as Business as Usual (BAU. The assessment is done using an Integrated Assessment Model.

II. LITERATURE REVIEW

A. Integrated Assessment Models

An integrated assessment model (IAM) combines various component models, utilizing mathematical representations of data from different fields of study. This interconnected system links information across multiple disciplines to create a comprehensive analytical framework. The links could be soft, hard or integrated. Soft-linked provides manual transfer of model results between modules. In the Hard-linked model, a reduced version of one model exchanges data with the primary model, with both running simultaneously. In an integrated model, all models run simultaneously through a unified mathematical approach. While a feedback loop is required from the world model, the world model used is based on the work of Sole et al. (2020). Interpretations of model simulation results were focused on the impact of the energy transition pathways on the Nigerian economy. It includes integrating Nigeria's input-output table in the economy module and modelling Nigeria's economic sector commercial relations through input-output analysis.

The need to build frameworks that capture features of real-world economics, which is crucial for meaningful policy intervention, has led to new economic approaches (Hafner et al., 2020).

Holistic frameworks and methodologies are required to assess the changes required for a sustainable energy transition. Integrated assessment models that incorporate various disciplines are required. This is to capture interactions between human and natural systems – which tend to be complex, dynamic, and highly non-linear- to provide helpful information for policymaking (Capellán-Pérez et al., 2020). Key attributes include – macroeconomics, energy resources, infrastructure, climate change, and social and environmental factors. Early models focused only on energy system interactions. Later models incorporated macroeconomic attributes to form energy-economy models. There have been calls for a new approach to overcoming assumptions in Computable General Equilibrium (CGE) and Dynamic Stochastic General Equilibrium (DSGE) – representative agents, rationality and optimizing behaviour (OECD, 2015; OECD, 2017).

Davidson (2014) summarised the key characteristics of an energy transition using integrated assessment models, as shown in Figure 1.

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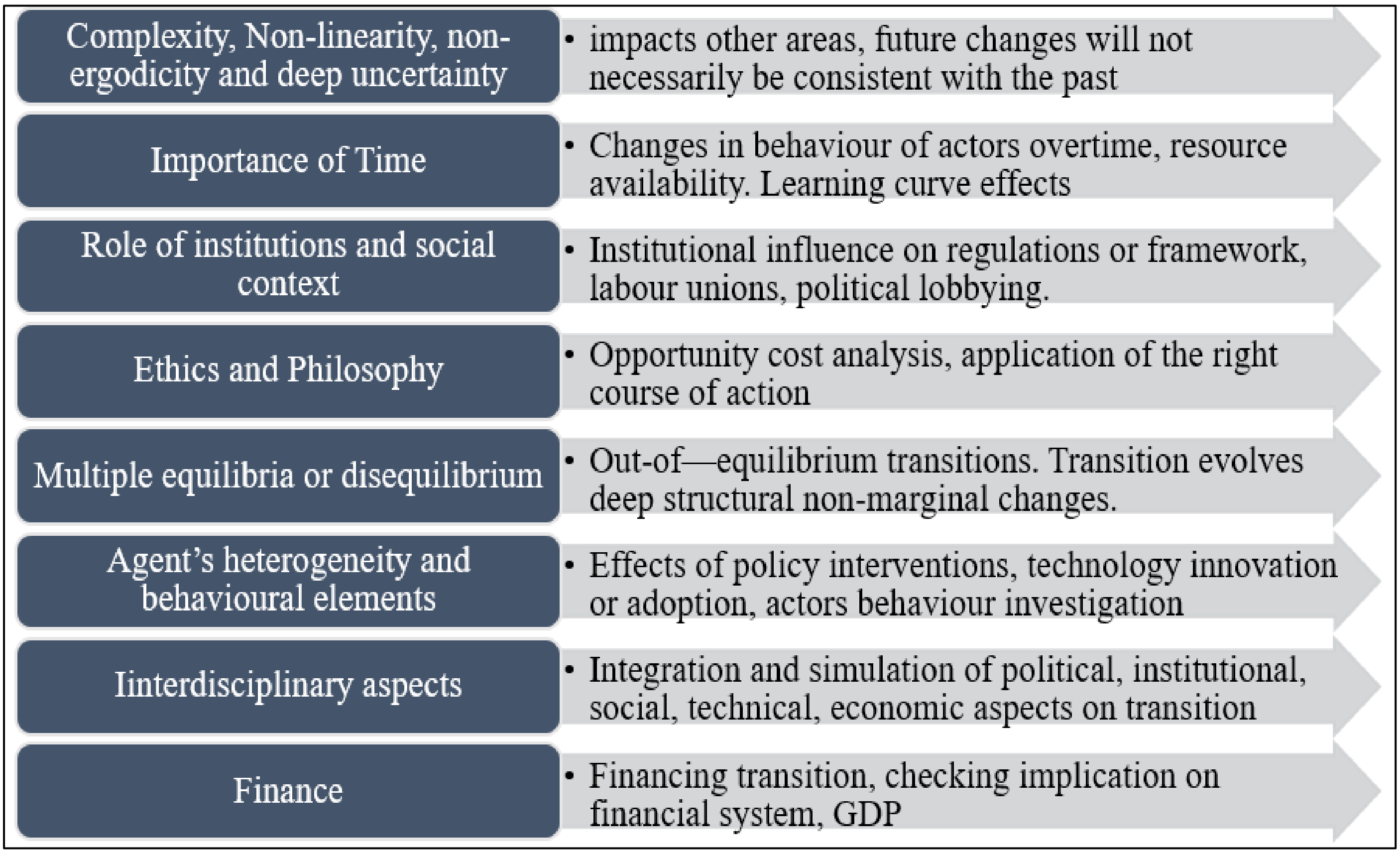

Fig 1: Key Characteristics of New Approach in Energy Transition Modeling

Different modelling approaches have been developed, and they can be broadly classified under general definitions of optimisation or simulation models and top-down/hybrid/bottom-up models (Scrieciu et al., 2013). Optimisation models rely on neoclassical economics and, therefore, support the assumptions of CGE. It assumes clearing markets through price adjustment, allowing full employment and productive capacity (Sterman et al., 2012). Furthermore, to meet the optimal growth assumptions, which are supply-led, adjustments to factors of production such as labour, capital, and technological changes are made. On the contrary, simulation models allow for the description of relationships between economy, energy, and climate models, thus allowing the examination of the propagation of disturbances into the system and evaluating different outcomes of policies. The pioneer World3 model of Limits to Growth (Meadows, 1972) is recognised as the most known contribution to simulation models. While optimisation models could be considered supply-led, simulation models could be regarded as demand-led with the potential to include supply as model constraints. Demand-led models are usually sustained in post-Keynesian economics, assuming disequilibrium, meaning non-clearing markets, demand-led growth, and supply constraints (Lavoie, 2014; Taylor et al., 2016). Demand-led models start by modelling demand, i.e. the direct and real expression of the productive factors capacity. Other examples of the non-equilibrium models are E3MG model (Pollitt et al, 2014), ICAM (Dowlatabadi, 1998), GTEM (Kemfert, 2005) AIM (Kainuma, 2003; Masui et al., 2006; Morita et al., 2003) and IMAGE (Alcamo et al., 1998; Bouwman et al., 2006; E. Stehfest et al., 2014).

In the Top-down models, macroeconomic effluences like policies are the essential drivers of the model outcome. An example is the DTI Energy model, where GDP and activity assumptions influence final energy demand in the system (Bhattacharyya, 2011). On the other hand, Bottom-up is driven by partial equilibrium in technology competition as a driver for energy demand in the energy system (Sole et al., 2020), as well as consumer demographics and preferences in the accounting system model. Examples are MARKAL, TIMES, EFOM, LEAP, MEDEE, MAED. The hybrid model combines detailed macroeconomics and energy views of technologies. Examples are NEMS, POLES, and WEM. (Bhattacharyya, 2011). While in the early times, top-down optimisation models were dominant, critical observations have been made to this approach. The assumption of perfect substitutability between factors has been widely criticised by ecological economics, which considers that complementarity better fits reality (Christensen, 1989; Daly & Farley, 2003; Stern, 1997). In addition, there is a lack of economic sectoral disaggregation, which does not allow models to capture the relevance of economic structure in energy-environment-economy interactions (De Haan, 2001; James et al.,1978). Moreover, optimisation is an unrealistic approach to modelling complex, dynamic systems in which feedbacks and time matter (Capellan-Perez, 2016; Uehara et al., 2013). Nevertheless, the majority of demand-led models account for a sequential structure instead of the feedback-rich structure of System Dynamic models.

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B. The Pymedeas Model

The pymedeas model is a simulation and hybrid, integrated assessment model. (Scrieciu et al., 2013). It is demand-led, disaggregated by sector, and based on a disequilibrium approach and Input-Output Analysis (IOA). By adopting a demand-led approach, pymedeas contributes to widening this demand-side body of literature. It is considered a more realistic procedure, as demand represents the economic activity deployed by the productive factors, whether in equilibrium or not. However, demand-led models tend to underestimate or not consider supply-side constraints, allowing GDP to grow unhindered. The pymedeas model's main contribution is the inclusion of supply constraints and climate change, which give feedback on the economy through energy availability and emissions (Sole et al., 2020). Input-Output Analysis (IOA) serves as the foundation for demand modelling in the economy model. This analytical method is regarded as a practical approach for evaluating direct and indirect impacts on production across various sectors within an economic framework. IOA also plays a significant role in understanding the dynamics of demand evolution, as noted by Leontief (1970) and Miller and Blair (2009). IOA also includes environmental hybrid modelling and has been combined with system dynamics in tripartite modelling of energy, economy and climate (Leontief, 1970; Miller and Blair, 2009). By using IOA to start the demand modelling, pymedeas not only can make a sectoral analysis of its results, but it also assumes disequilibrium, and it can capture structural conditioners in transitions, something that is often missing from macroeconomic modelling. IOT does not make assumptions on equilibrium in the goods market or the factors market but reveals the actual nature of economic evolution. Trying to model disequilibrium in a factors market necessarily leads to making unrealistic assumptions. For instance, modelling labour supply as a positive function of wages implicitly considers perfect mobility of labour and/or the societal capacity to sustain a significant share of the inactive population permanently. pymedeas, on the contrary, considers disequilibrium in the factors market as given in the data, treating each economic variable according to implicit unemployment and under-utilisation of capital. The model overcomes the main limitations of energy-economy-environment modelling that rely on optimisation, sequential structure, and neoclassic production function regardless of disequilibrium and economic structure and lacks biophysical constraints. pymedeas_eu Economy module has contributed to the now-emerging field of ecological macroeconomics (Sole et al., 2020; Hardt and O'Neill, 2017; Rezai and Stagl, 2016). Figure 2 shows the one-way integration between the world and the Nigeria model, while Figure 3 shows the link between the various modules of the Integrated Assessment model in pymedeas.

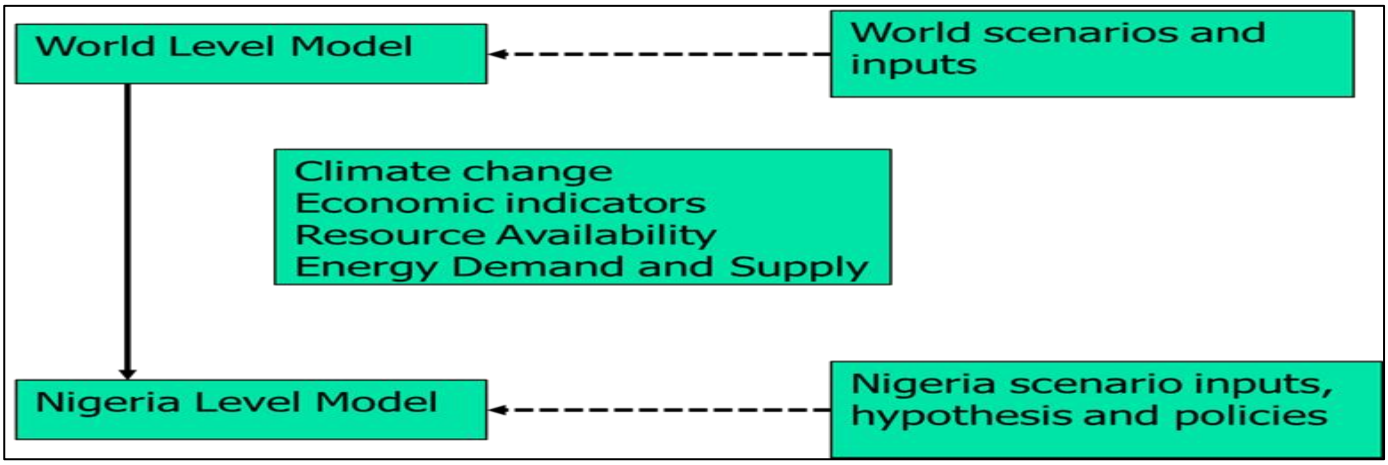

Fig 2: One Way Integration at Geographical Levels

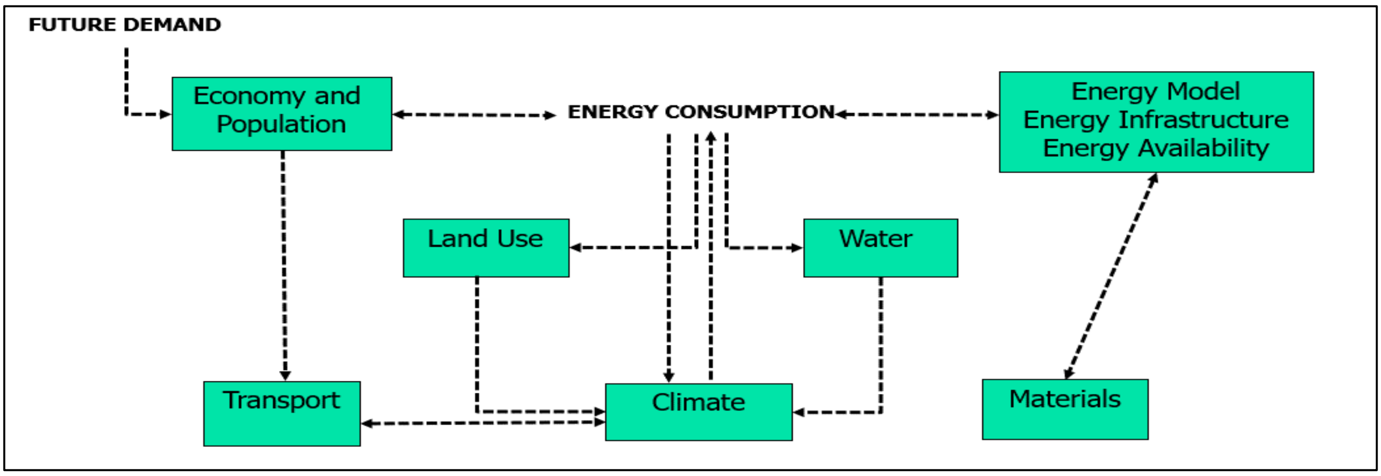

Fig 3: Pymedeas Module with Links

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III. METHODOLOGY

Pymedeas was selected as the dynamic Integrated Assessment Modelling (IAM) environment. Pymedeas is an Open-source software written in Python 3. It is a transparent, user-friendly, and community-based tool developed to explore the transition to a low-carbon socio-economy. The Open-source nature of the code is guaranteed by an MIT license, while its transparency is guaranteed by detailed and extensive documentation of the code. The GIT repository allows for contributions from any third party and adaptation to other economic regions. The Graphical User Interface (GUI) for plotting simulation results and for visualization and comparison of independent simulations supports user-friendliness. The pymedeas_Nigeria model is nested to the pymedeas_world model developed by Sole et al. (2020).

Data for adaptation to Nigeria's Economic model was sourced from the World Input-Output Database (WIOD), which spanned from 1995 to 2014 and adjusted using data from the Nigerian Bureau of Statistics (NBS); Energy data was mainly sourced from the International Energy Agency (IEA), while climate data was based on the Representative Concentration Pathway (RCP) models. The change of accountability of IOT data from 2015 in the WIOD database meant the original pymedeas was set up only to 2014. Sectorial aggregation of Nigerian Input-Output Tables (IOTs) was done, and the estimate of the coefficients of the final demand function for Nigeria IOT was obtained using panel data regression. Technical coefficients of the IOTs were estimated following the Leontief Matrix approach. In the economic model, the Leontief Matrix determines how many units of Sector A product, for example, are required to produce Sector B. For each time step, the GDP is estimated, and the value-add is distributed to each sector. The sectorial demand is therefore estimated, and sectoral energy demand is estimated using the supplied energy intensities. The aggregate energy demand is compared with the energy supply in the energy model. The desired GDP is fulfilled if the total energy supply is sufficient to meet demand. Otherwise, the estimated GDP that the supply can meet is estimated and returned as simulated GDP. See Figure 4.

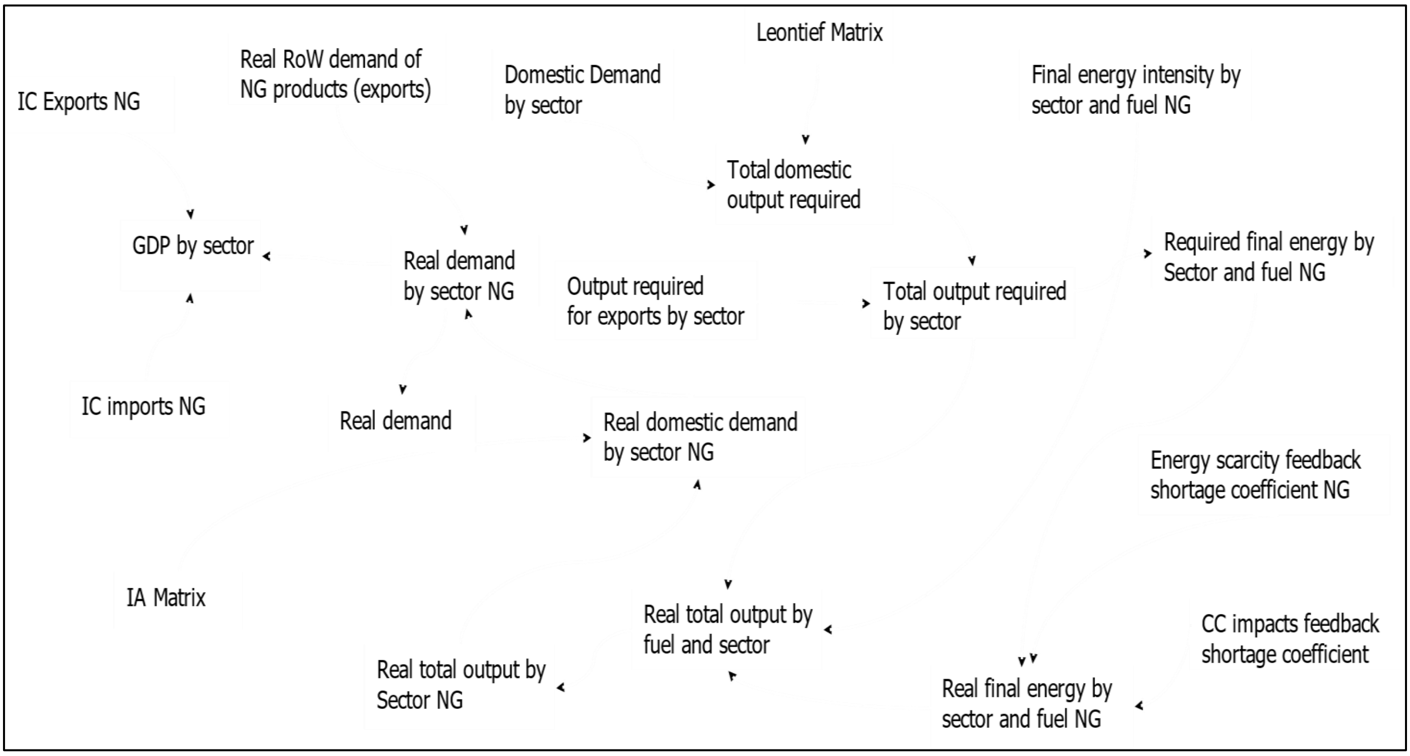

Fig 4: Simplified System Dynamic Flowchart for Input-Output in MEDEAS-NG

Using the WoodMac database, maximum extraction curves for Nigeria's fossil fuel supply from 1995 to 2050 were modelled. The model was simulated and calibrated against the historical monetary performance (GDP_Ng) (1995 – 2024). The extension to 2024 was to account for the impact of COVID-19 on the economy. The results were compared using Root Mean Square Deviation (RMSD).

A. Scenario Parametrisation

Reviewing Nigerian energy policy and exiting shared socioeconomic pathways (SSPs) has parameterized the transition pathways. Table 1 shows some of the parameters of the studied transition pathways.

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Table 1: Transition Scenario Design

Policy	BAU	NZP
Start Year of Biofuels for electricity	2035	2025
Leaving of Fossil in underground	2035 (0% for Oil, gas; 90% for coal)	2025 (75% for Oil, 0% for gas; 90% for coal)
Target year for phase-out of oil for electricity	2050	2030
Transport – Gas share for inland transportation	10% increase to 2050	30% increase to 2050
Climate Impact	RCP 8.5	RCP 2.6

B. Model Prediction

Simulation and investigation of future economic, energy and environmental performance were carried out on the calibrated model for each alternative transition pathway using RMSD.

IV. RESULTS AND ANALYSIS

A. Model Calibration

The simulated GDP for Nigeria between 1995 and 2014 was compared with the desired GDP in the same timeframe using Root Mean Square Deviation (RMSD) (Figure 5). The RMSD was estimated at 0.07. Visual observation shows a fair to good calibration except for the period between 2009 and 2011.

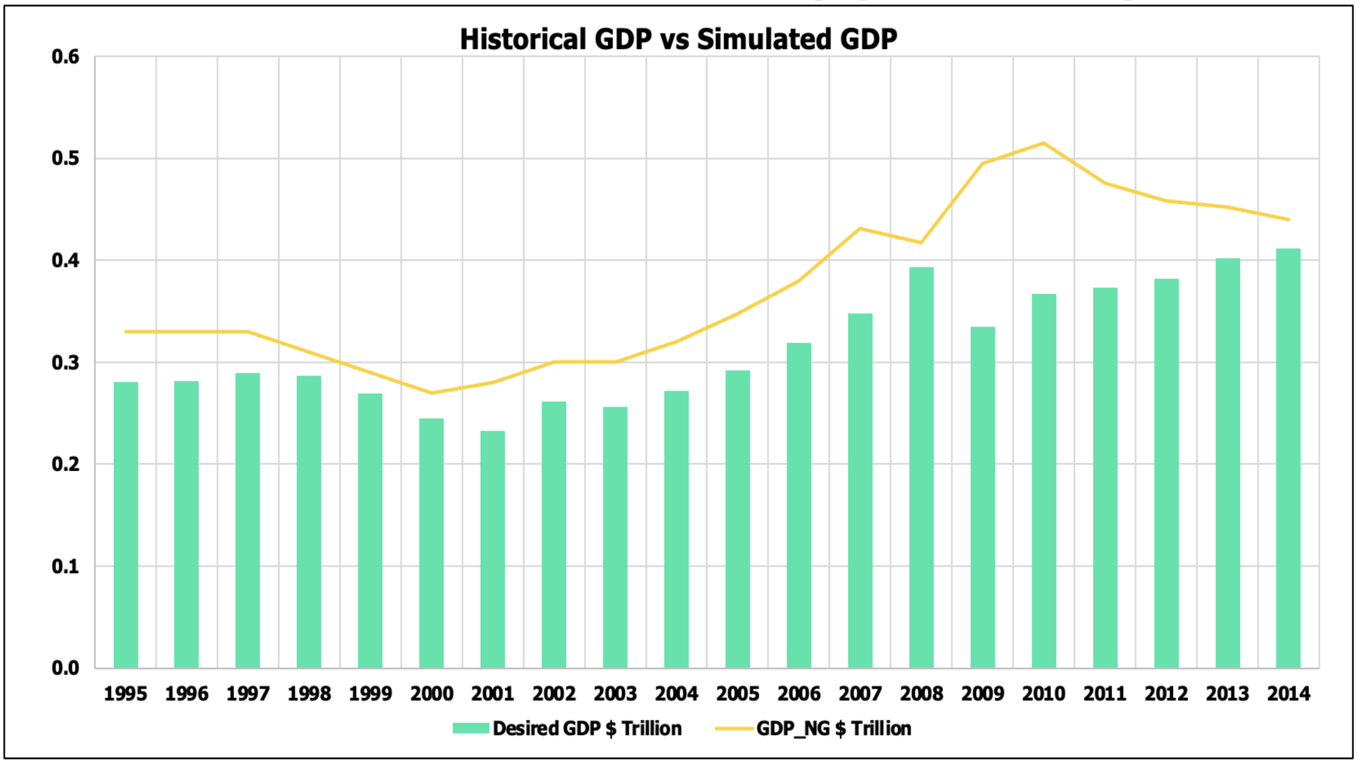

Fig 5: Historical GDP 2010 vs Simulated GDP for Nigeria

In comparing the desired GDP with the simulated GDP at the world level, the RMSD was estimated at 1.14 (Figure 5), reflecting the difference in the scale of the GDP at the world and country levels.

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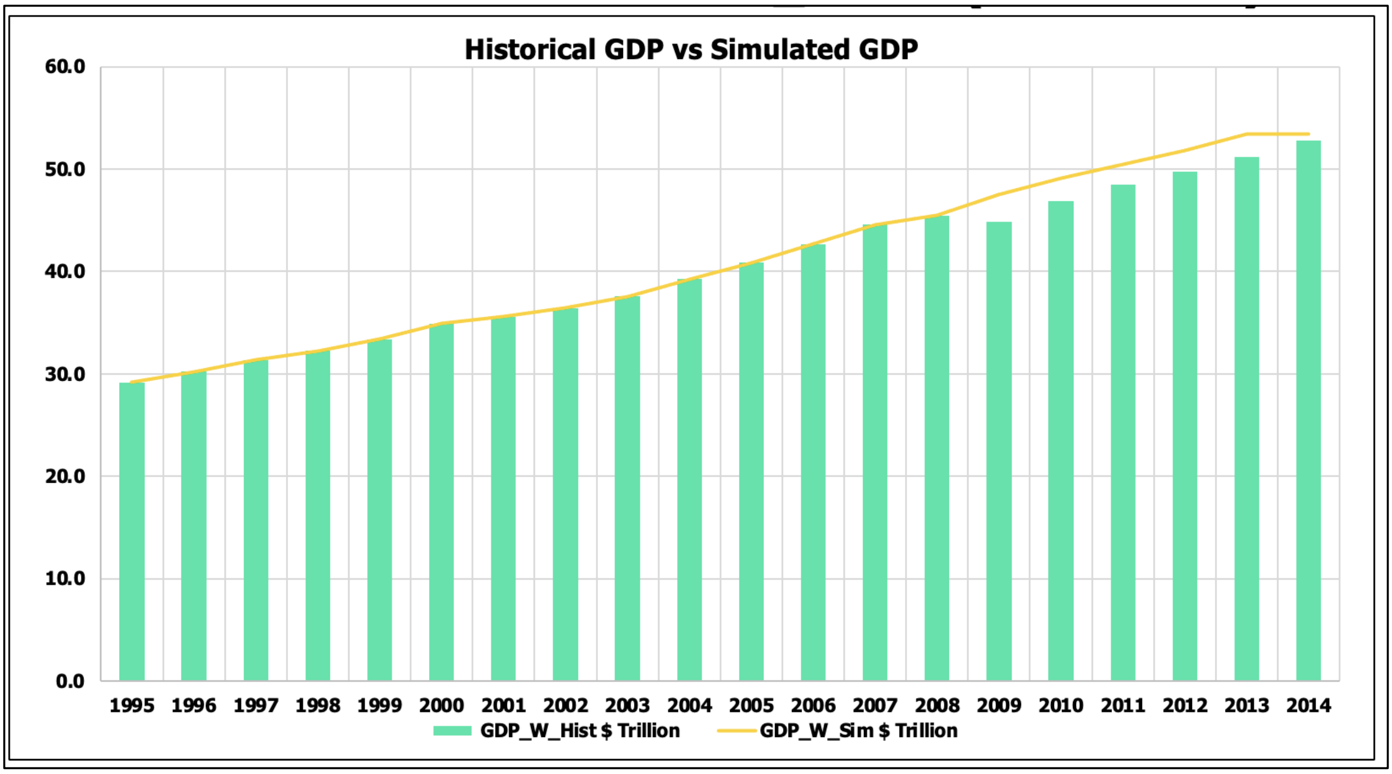

Fig 6: Historical GDP vs Simulated GDP for World

World GDP is observed to grow at a rate of 3.3% (Figure 6). When comparing Nigeria's historical contribution to world GDP with the simulated historical contribution, the percentage contribution remained relatively constant at about 0.65%, as previously observed in the historical period (2000-2014) (Figure 7).

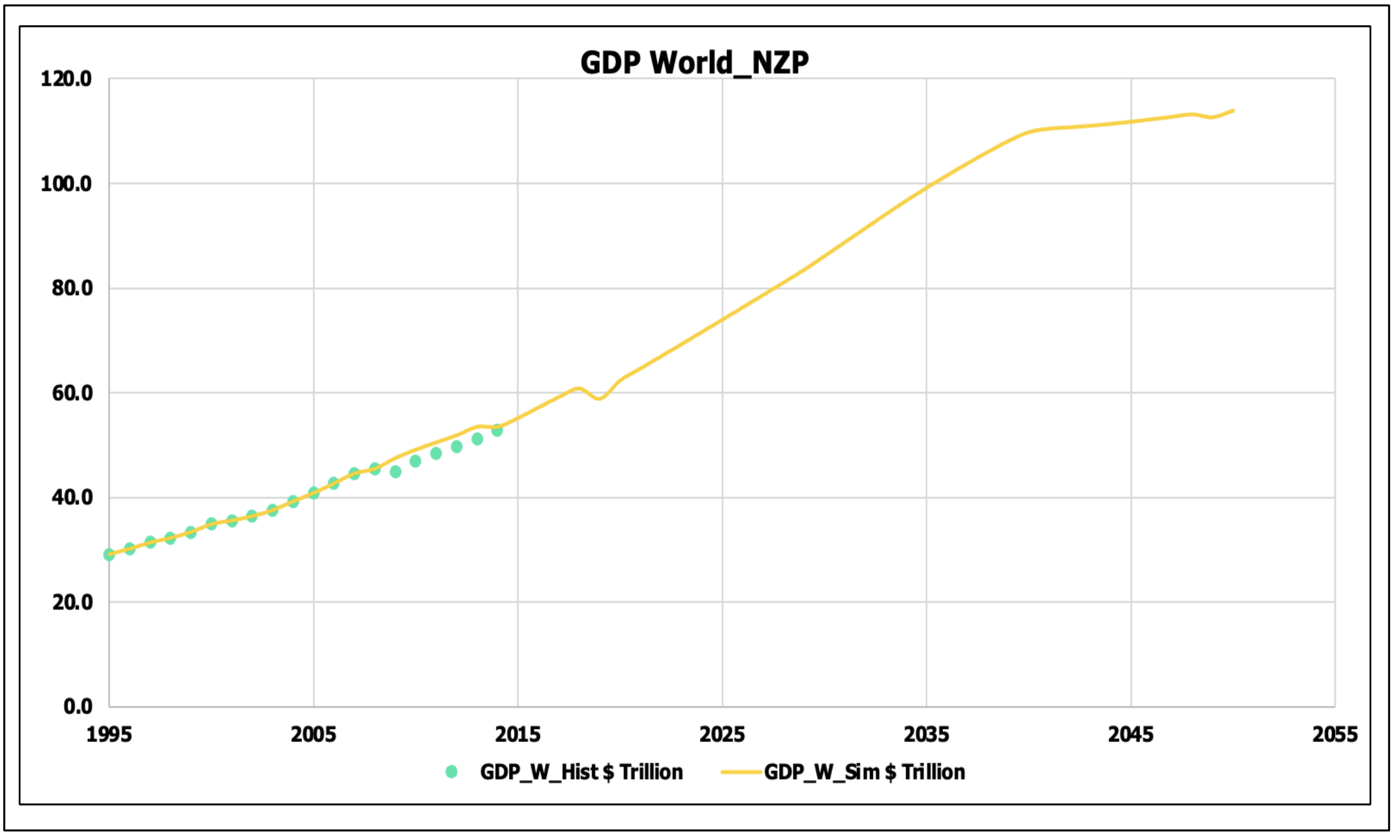

Fig 7: World GDP Trend

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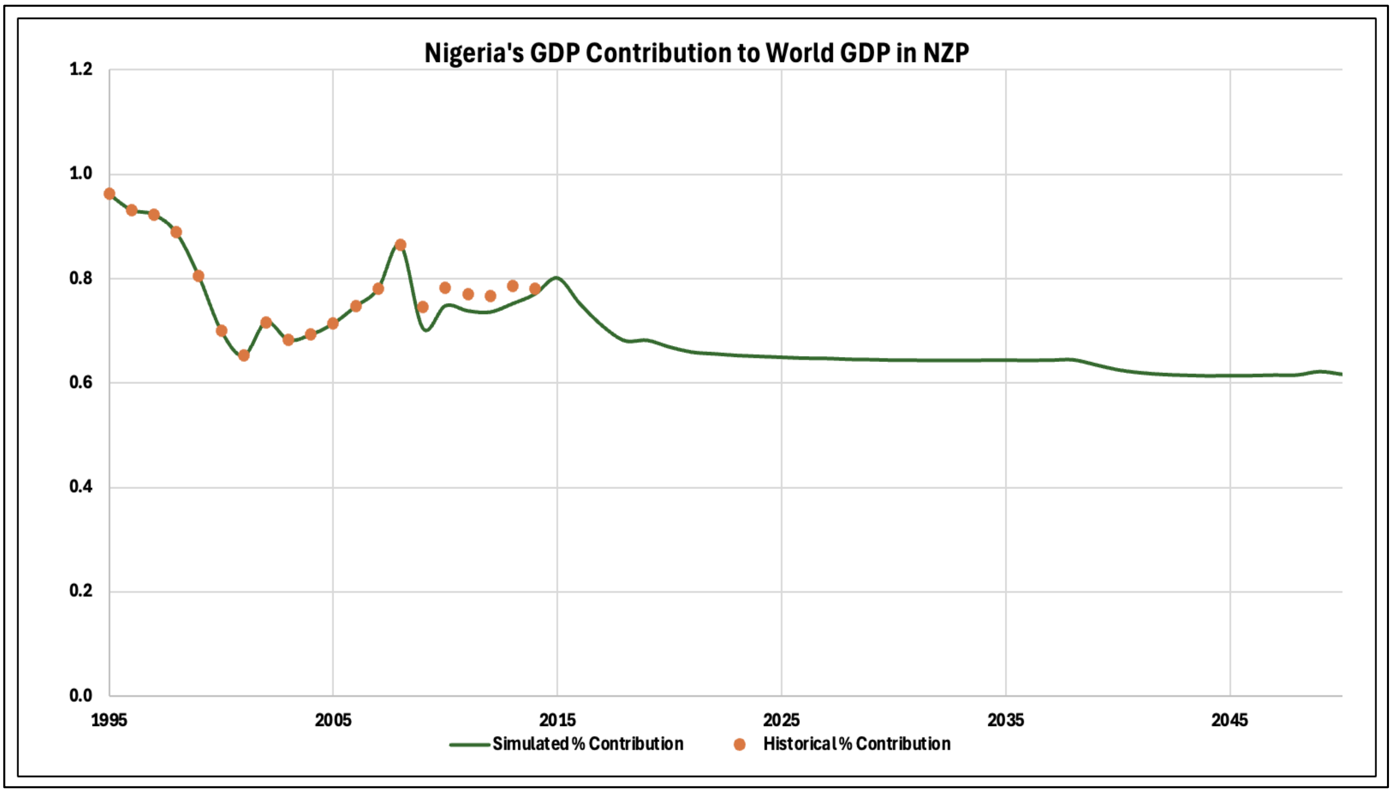

Fig 8: Nigeria GDP Contribution to World GDP

B. Non-Renewable (BAU) vs Renewable Pathways (NZP)

GDP growth for the Renewable Energy pathway, also known as the Net-Zero Pathway (NZP), is slow at -3% in early years compared to an increase of about 2% in the Non-Renewable Energy Pathway, also known as Business-As-Usual (BAU). It peaks up and outpaces BAU from 2038. Figure 8 compares GDP in the BAU scenario with the NZP scenario. It will take longer for net-zero policies to take effect compared to the already established BAU.

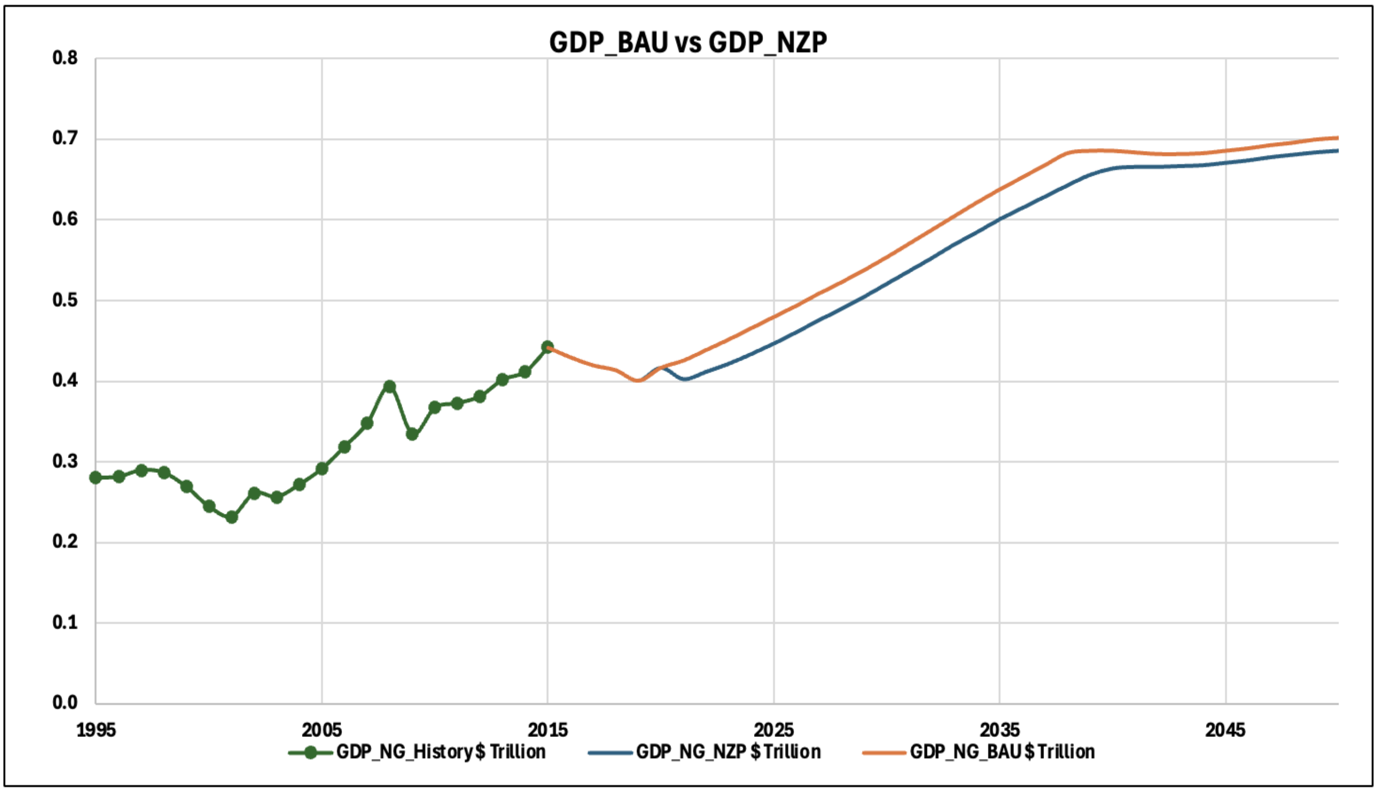

Fig 9: Simulated GDP for Nigeria (BAU vs NZP)

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V. DISCUSSION OF FINDINGS

This research presents pymedeas, a novel open-source modelling tool programmed in Python, to the Nigerian Energy transition modelling community for energy-economy-environment analysis. The MARKAL family is considered the most widely used and recognized among bottom-up energy models, as noted by Bhattacharyya (2011). Its evolution, TIMES, was developed by the IEA-ETSAP, along with the MESSAGE set of models, as described by Schrattenholzer in 1983. Diemuodeke et al. (2024) employed LEAP for Nigeria's Deep Decarbonization Pathways, considering only three models: energy, emission, and economics. This study complements bottom-up approaches by offering a top-down perspective using aggregated variables.

The research introduces several innovations using pymedeas. It integrates system dynamics with Nigeria's Input-Output analysis to examine the energy system's evolution under environmental and biophysical constraints. Additionally, it develops scenarios and hypotheses based on the Nigerian Energy Transition Plan Policies outlined by the National Council on Climate Change, enabling projections of the energy system's future evolution. The study compares the Business As Usual Scenario (BAU) with the Net-Zero Pathway (NZP). The IAM also allows for modelling the impact of supply constraints on the chosen transition pathway.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. Limitations

The limitation of the current research work is data availability. Given the number of sectors and modules modelled in the Integrated Assessment Model (IAM), continuous data refinement is required when model prediction deviates from policy direction and definition. The IOT tables used in the model calibration spanned only 1995-2014 due to the change in WIOD accountability from 2015. IOT should be extended to 2024, incorporating the impact of COVID-19, especially in the growth of the digital sector of the economy. The effect was exogenously modelled by adjusting model variables to allow the simulated GDP to match the historical GDP. Nigeria Nationally Determined Contributions (NDC) at COP26 was revised to the 2060 Net-Zero target date. Further work should include extending the simulation period to 2060.

B. Conclusion

An Integrated Assessment Model (IAM) for Nigeria has been built using the pymedeas modelling platform and simulated using a Python programming environment (Anaconda). The IAM integrates seven socioeconomic, energy, and environmental modules at the Nigerian and world levels. The Nigerian economic level uses input-output tables aggregated to 14 sectors across 20 years (1995-2014) to calibrate the IAM. Hypothesis testing has been designed to test the impact of two modified Shared Socioeconomic Pathways (SSPs)- Non-Renewable Pathway (BAU) and Renewable Energy Pathway (NZP), representing different energy transition pathways on Nigeria's GDP.

This work provides a complementary approach to the existing body of literature on Shared Socioeconomic Pathways (SSP). The model's modularity in terms of structure and functions means the user could conduct detailed investigations on a range of energy transition subjects for Nigeria.

C. Recommendations

This Integrated Assessment Model (IAM) is recommended for use in reviewing energy transition policies and their impact on Nigeria's socioeconomic, energy system, and environment. The system dynamic feedback loop executed within the pymedeas allows for dynamic testing of exogenous policies and endogenous feedback within the pymedeas. Each module can be studied as a standalone, keeping policies in other modules constant and checking the impact on various aspects of the shared socioeconomic pathways.

Nigeria should pursue a policy that allows continued development of fossil fuels at the levels captured in the BAU with climate impact mitigations such as reducing gas flaring and CCUS. The above should be balanced by early and structured investment in centralized renewable energy infrastructures.

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