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Making hay while the sun shines: Energy security pathway for Africa

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ABSTRACT

Should Africa rather delay investments in renewable energy given their trivial contributions to global greenhouse gas emissions? This is strongly discouraged given the existing benefits of increased renewable energy investments in an African economy. Nigeria, the leading African economy is adopted as a representative to illustrate the prospects of improved (renewable) energy security in Africa. This study develops a dynamic recursive general equilibrium model to evaluate the prospects of renewable energy investment paths for Africa towards improving its energy security levels. Unlike other competing models, this model allows businesses to dynamically substitute between intermediate renewable energy and fossil fuel products, thus, taking active steps towards achieving a green economy. The results show that present economic welfare will be sacrificed for future welfare benefits and improved energy security. This confirms the transitioning of an economy from a lower steady state to a higher steady state path as postulated by the Solow model. However, a sustained gradual investment in the renewable energy sector yields the least welfare loss as the economy transitions through its energy security path. The one-off policy design produces relatively higher results in the immediate future while the sustained gradual incremental path smoothens these results into the far future. The results confirm that Africa's demand for renewable energies substantially outweighs its supply, thereby suggesting a potential and non-trivial market for renewable energies, nonetheless. Results-based policies that are geared towards improving energy security are formulated for the African economies.

1. Introduction

In a world of growing efforts towards renewable energies while abandoning fossil fuel energies due to environmental concerns (Zhang, et al., 2020; Okorie and Lin, 2022c), every economy and continent must partake in this noble goal. Despite the country-level and/or continental-level contributions to global emissions, these efforts ought to be collective rather than individual in achieving the targeted global climate agreed outcome (Okorie and Wesseh, 2023). After all, the impacts of global climate change are rather collective than selective. In the African setting, the affordability of basic energies, mainly electricity, has become a rising issue against the existing clean and renewable energy availability issues. A major chunk of the agent's income goes to energy use, thereby making energy expenditure catastrophic as opposed to health expenditures (Okorie and Lin, 2022a). Generally, energy security, both affordability and availability, is a serious challenge in the developing economies of Africa (Adedeji et al., 2024; Ofosu-Peasah et al., 2021, 2024). To this end, this study takes the novel and leading role in investigating the welfare, energy and environmental implications of a top-down sectoral investment strategy in renewable energy mix, towards carbon neutrality and decarbonization, in Africa. Nigeria, the leading African economy, is used as a case study under investigation for developing the different energy security pathways. In contribution, this study proposes a dynamic recursive computable general equilibrium (CGE) model that captures the dynamic substitutability of energy products in the production processes of business, as an economic agent. This implies that over the years, a business unit can dynamically decide the proportion of renewable and fossil fuel energy products to use in its production activities. By so doing, they actively participate in achieving the global carbon emission mitigation targets. Furthermore, this model can evaluate and present the economic, environmental sustainability, energy security, and welfare dynamic effects of economic policies in an economy.

A top-down investment strategy seeks to identify an economic sector

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(or several economic sectors) or subsectors with growth potential that will outperform other sectors or subsectors and invest heavily in the businesses and industries in such sectors or subsectors. This is targeted at changing the business conditions by shifting the market due to the focused investment in such sector or subsector. The renewable energy market in Africa is untapped with abundant renewable energy resources and the potential to outgrow and outperform many sectors and subsectors (Okorie and Lin, 2022b). A substantial fraction of renewable energy products like electric cars, solar energy panel equipment, high-tech renewable energy equipment, etc., are produced abroad (outside Africa) and imported into African economies with high and significant import tariffs. As such, developing the renewable energy sector of Africa is fundamentally key to achieving import substitution industrialization, economic growth and developments amidst the carbon neutrality and decarbonization advantages of renewable energies. These renewable energy products, if produced in Africa, can compete with every other foreign product due to better revealed comparative advantages like abundant resources, relatively cheap labour supply rates, etc., (Gelb et al., 2016; Stuart, 2022; Okorie and Lin, 2022b). In addition, high-tech exports of Africa will increase significantly towards achieving and promoting the trade goals in Africa, even the AfCFTA (African Continental Free Trade Area) policy of the fifty-five (55) African Union (AU) countries.

Based on the information from the World Development Indicators (WDI), Table 1 shows the average percentage of the population that has access to electricity and clean energy technologies for Nigeria, Africa, and the Rest of the World (ROW) for the past decade. Based on these data, one could see the need to improve the level of energy security in Nigeria and Africa in general. Based on the latest updated information in the WDI database, the average renewable energy production proportions for the African economies are about 36.04%, 22.30%, 5.53%, 50.82%, and 25.52% of Africa's total electricity production is from hydroelectric sources, natural gas sources, nuclear sources, coal sources, and oil sources respectively as at 2015 (the last updated period). As such, it is clear that renewable energy production in Africa is lagging and efforts are required to improve the availability of energy products in the economies of Africa. There is an urgent need to boost Africa's renewable energy production as an instrument towards enhancing Africa's energy security state and contribute towards achieving the global greenhouse gas emission targets to mitigate global warming and its consequences on life and human activities.

Renewable energy investments in Africa equally promote Africa's renewable energy transitioning agenda and reduce the emissions of greenhouse gasses. Several instruments like carbon taxes, carbon trading, renewable energy subsidies, green bonds, etc have been developed and proposed to help economies towards achieving decarbonization, carbon neutrality, and net-zero (Okorie and Wesseh, 2024; Guo et al., 2020; Li et al., 2017; Lin and Jiang, 2011). Existing studies fail to evaluate and discuss (renewable) energy security pathways for Africa towards its renewable energy transition. This pathway includes both the accessibility and affordability of energy products in Africa. Secondly, existing studies fail to capture the substitutability dynamics of renewable energy products for fossil fuels within the production processes and activities of businesses. These are the major research gaps this study seeks to fill in the body of existing studies on renewable energy discussions. On these bases, this study investigates the renewable energy path for Africa towards improving and achieving energy security for the continent. The empirical results reveal that capital investments in renewable energy are capable of achieving and improving the level of energy security in Nigeria, a leading African economy. This increased capital investment in renewable energy security suggests that the economic agents sacrifice their present welfare for improved future welfare benefits. At the end of the ten (10) year simulation period, the result shows that moves closer and transitioning into renewable energy-based economies and achieving substantial energy security improvements.

The contributions of this study are as follows; firstly, this study takes a novelty step, beyond other existing studies, to evaluate the energy security pathways and their implications on environmental sustainability and economic welfare for Africa given its trivial global greenhouse gas emission contributions. Secondly, this study takes an economy-wide approach to propose a dynamic recursive computable general equilibrium model that accounts for the concern raised in Okorie (2021) that the intermediate input demand for energy products, within the production processes, is capital-dependent and driven instead of being treated as an independent and complementary factor input in other general equilibrium models (Burniaux and Truong, 2022; Fujimori et al., 2017). That is to say that the use of energy products by industries is driven by the levels of capital and technology employed in the production processes. Thirdly, the proposed model accounts for the substitutability between fossil fuel and renewable energy intermediate input demands by modelling them as close substitute goods. This allows all domestic economic agents to make a choice or decision between these substitutes and to further take advantage of renewable energy products as alternatives and substitutes for fossil fuel energy products. Thereby leading to collective efforts towards achieving the economy's carbon emission reduction targets, global warming mitigation, and improving the quality & sustainability of the environment. The rest of this study is sectioned into Literature Review (2.0), Empirical Strategy (3.0), Results and Discussions (4.0) and Conclusions (5.0).

2. Literature review

The role of investments in improving and developing the level of renewable energies in an economy cannot be overemphasized (Xu et al., 2024). In the African setting, Menyeh and Acheampong (2024) show that crowdfunding is an investment alternative for renewable energy in Africa. Their study shows empirical evidence that supports crowdfunding in improving the level of renewable energy investments using Ghana as a case study. The benefits of renewable investments are not only applicable on a macroeconomic level but also on microeconomic levels. Azhgaliyeva et al. (2024) show that feed-in tariffs boost firms' investment in renewable energies, particularly solar energy against wind, geothermal, biomass and hydro energy options. Notwithstanding, the good news is that renewable energy investments also play key microeconomic roles in an economy. At the very least, the preferences of the government are also shown to substantially affect renewable energy technological development and innovation (Lin and Wang, 2024).

While looking to improve the level of renewable energy in an economy, environmental policies play vital roles. Ji et al. (2024) opined that carbon price policies, subsidies, and green trading policies have substantial positive effects on renewable energy investments. This evidence is based on the economy of China. They noted that in some cases or scenarios, an economy is better off adopting green trading policies instead of subsidy policies. In addition to these factors, green funding has also been found to be significant in harnessing renewable energy investment in the Chinese economy while the roles of geopolitical risk factors on renewable energy investments should not be ignored (Zhao et al., 2024). Yadav et al. (2024) seem to agree with the roles of geopolitical risk factors in the level of renewable energy investments but added that the governance quality and strategic green finance are robust in boosting the level of renewable energy investments in an economy.

Green assets like green bonds, green finances, green trading, green funding, etc. also have substantial improvement effects on improving renewable energy investments in an economy (Ji et al., 2024; Yadav et al., 2024). Yadav et al. (2024) noted that green finance and quality governance moderate the effects of renewable energy investment on the emission of greenhouse gasses in an economy. Chen et al. (2024) share this view that renewable energy investments mitigate climate change. However, financial developments, in addition to renewable energy investments, mitigate climate change. This holds for both OECD and non-OECD countries with the existence of a long-term co-integrating relationship between renewable energy investments and climate change. For these OECD countries, energy innovation investments improve their level of renewable energies with significant heterogeneous effects.

On the note of whether or not to use equity or debt investment financing in the renewable energy sector, Wen et al. (2024) provide empirical evidence in support of equity investment financing for the renewable energy sector against debt financing alternatives. Similarly, formal finance, environmental higher education, and energy security risks strongly influence renewable energy investments (Zeng et al., 2024). Guetlein and Schleich (2024) added that higher rates of return and shares of self-consumption increase private investments in renewable energy communities or sectors. Likewise, public investment in renewable energy is not left behind. Yuen and Yuen (2024) showed that geopolitical risks and uncertainties increase public renewable investments. On the other hand, issuing carbon-neutral bonds is also capable of increasing low-carbon investments to the tune of about 4.7% in the renewable energy sector (Jia et al., 2024).

Ebaidalla (2024) made contributions in terms of the factors that affect the level of renewable energy investments in an economy. This study added that among these factors that affect renewable energy investment in an economy, including private and public investments, are technological innovations and trade openness. However, taxation acts as a deterrent to renewable energy investments in an economy. Fabra et al. (2024) rather explored the effects of renewable energy investments on employment and unemployment in an economy. They found evidence that renewable energy investments, public and private, have a substantial influence on local employment and unemployment. Particularly, the effects of solar renewable energy investments on employment and unemployment outweigh that of wind renewable energy investments. These renewable energy investments further improve the residents' per capita income as well as raise the government's spending. Similarly, green industrial policies are also capable of boosting the level of renewable energy investments in an economy with heterogeneous impacts. The effects seem to be less pronounced in OECD countries relative to other countries. Specifically for private renewable energy investments, green loans have significant improvement effects while the green tax could only have positive effects in the long run (Zhang and Guo, 2024).

Narrowing down to Africa-specific studies, given Africa's abundant minerals and resources (Weldegiorgis, 2023), Africa can improve its energy security by transforming waste into energy through biogas (Surroop et al., 2019) and solar sources (Brunet et al., 2022). However, international disruptions of energy supplies and non-state attacks on energy infrastructures hinder Africa's energy security achievements, at least for North African countries (Lacher and Kumetat, 2011). These challenges also affect water and food security given their nexus in Africa (Nkiaka et al., 2021, 2023; Muhirwa et al., 2022; Okumu et al., 2021; Gulati et al., 2013). In Africa, renewable energy is also correlated with food security (He et al., 2024; Mperejekumana et al., 2024). Ofosu-Peasah et al. (2024, 2021) and Adedeji et al. (2024) posit that the state of energy security in (west) Africa is characterized by conventional factors (reliability, availability and affordability), unconventional factors (sustainability and regional energy pools), and priority factors (security and energy sector investments). Tete et al. (2023) added that while Senegal and Mali are the most and least energy security economies of Africa respectively, no African country is entirely energy secured based on all the evaluation criteria. Sebitosi (2008) and Bellos (2018) show that energy efficiency guarantees that South Africa meets its energy security targets while measuring and managing the tensions between energy security and transition.

In a nutshell, these studies examined the factors that influence the levels of both private and public renewable energy investments in an economy and how these levels of renewable energy investments affect other economic factors in an economy. However, they fail to develop a path for renewable energy investments in an economy and how these levels of renewable energy investments affect the economy's output, energy security, employment, aggregate prices, economic agent's welfare, productivity, carbon mitigation, carbon intensity, and every other sector of the economy. Secondly, this study proposes a dynamic recursive model that captures the dynamic substitutability between renewable energies and fossil fuels in the production processes of businesses. These are the problems this study seeks to solve to fill this gap in the existing body of literature on renewable energy investments. Therefore, this forms the contribution and significance of this study.

3. Empirical strategy

3.1. The dynamic recursive EEICGE model

The Energy and Environment Integrated Computable General Equilibrium (EEICGE) model has been developed and applied for policy evaluations and simulations in Africa's settings (Okorie and Lin, 2024; Okorie and Wesseh, 2024). Particularly, the EEICGE model has been used to evaluate energy and environmental policy implications in an African economy, among other policy implications. However, both EEICGE V.1.0 (Okorie and Lin, 2024) and EEICGE V.2.0 (Okorie and Wesseh, 2024) are static models. As such, they are only capable of comparative static policy evaluations in a single period and do not reveal the multiplier effect of current policies into the future. This shortcoming calls for the Dynamic EEICGE (V.3.0 and V.4.0) model which is capable of depicting current and future periods comparative statics of policy interventions. The Dynamic EEICGE V.4.0 is an extension of V.3.0. on carbon trading and pricing markets within an economy. This study develops and applies the Dynamic EEICGE V.4.0 model to explore Africa's pathway towards energy security.

Particularly, the dynamic recursive EEICGE model models value added as a function of labour and capital-energy nested factor inputs. Thereby, making the use of energy within the production activities to be dependent and driven by the level of capital and technology in an industry. This modelling approach follows the argument of Okorie (2021) against modelling energy inputs as complementary and independent intermediate factor inputs for production (Burniaux and Truong, 2022; Fujimori et al., 2017). By implication, modelling energy inputs as independent factor inputs suggests that energy is a primary factor input used in production activities. On the contrary, this is not the case since energy use within the production processes is an intermediate factor input and is dependent on capital and technological levels (Okorie, 2021). Furthermore, the dynamic recursive EEICGE model accounts for the substitutability between fossil fuel energy intermediate inputs and renewable energy intermediate inputs against being modelled as complementary inputs of production. Intermediate energy inputs are modelled as a substitute constant elasticity of substitution function between composite renewable energy-mix and composite fossil fuel. This brings the EEICGE model further to reality wherein renewable energy products are used as substitutes and alternatives to fossil fuel energy products. Gone are the days when only petrol, diesel, or gas-powered automobiles and locomotives. These days, electricity (howbeit from renewable energy sources like solar, wind, etc) powers automobiles and locomotives with significantly reduced or no carbon emissions. This substitutability, as allowed in the dynamic recursive EEICGE model, is key towards an economy-wide reduction of greenhouse gas emissions by all the domestic economic agents. These are the key methodological contributions of this study.

$$CEN_{jt} = A_j^{EN}\left[\beta_j^{EN} CEL_{jt}^{-\rho_j^{EN}} + \left(1-\beta_j^{EN}\right) CFO_{jt}^{-\rho_j^{EN}}\right]^{\left(\rho_j^{EN}\right)^{-1}} \tag{1}$$

$$P_{jt}^{CEN} CEN_{jt} = P_{jt}^{CEL} CEL_{jt} + P_{jt}^{CFO} CFO_{jt} \tag{2}$$

For a typical African economy, the composite energy input demand of industry or sector j at time t, CEN_{jt}, is defined as a composition of the aggregate or composite electricity, CEL_{jt}, and fossil fuel, CFO_{jt}, energies, shown in equation (1). These energy inputs are necessary for profit maximization sectors to produce desired output levels at a minimized cost. Moreover, these input demands are intermediate and not primary input demands (Okorie, 2021). As such, it is likely that some sectors can still produce their desired output, maximize profit, and minimize cost with solely the primary inputs. These intermediate input demands for energy products are purchased at different input prices as illustrated in equation (2), where P_{jt}^{i} is the industry j's price of good i at time t.

$$CEL_{jt} = A_j^{EL}\left[\beta_j^{EL}CRE_{jt}^{-\rho_j^{EL}} + \left(1-\beta_j^{EL}\right)CNRE_{jt}^{-\rho_j^{EL}}\right]^{\left(\rho_j^{EL}\right)^{-1}} \tag{3}$$

$$CFO_{jt} = A_j^{CFO}\left[\beta_j^{CFO}ROIL_{jt}^{-\rho_j^{CFO}} + \left(1-\beta_j^{CFO}\right)BFS_{jt}^{-\rho_j^{CFO}}\right]^{\left(\rho_j^{CFO}\right)^{-1}} \tag{4}$$

Africa's electricity production is aggregately from composite renewable energies, CRE_{jt}, and composite nonrenewable energies, $CNRE_{jt}$, captured in equation (3). The fraction of electricity production from renewable or clean sources may differ across different African economies (Okorie and Lin, 2022b). However, a common stylized fact is that this fraction is significantly below the fraction of electricity production from nonrenewable sources, including fossil fuels. This does not imply that Africa contributes significantly to global emissions. On the contrary, Africa, as a continent, is the least contributor to global carbon emissions (AlJazeera, 2023). Africa's contribution is about 4% despite having about 17% of the world's population. Nonetheless, Africa does not need to wait till they contribute significantly to global emissions to take action towards embracing clean and renewables, decarbonization, net-zero, etc. Africa should and ought to make hay while the sun shines. Conversely, Africa is endowed with several abundant natural resources, most of which serve as fossil energy sources. Equation (4) captures the intermediate input demand for composite fossil energy products by sector j at time t, CFS_{jt}, as a function of two disaggregated fossil energies, the refined oil, $ROIL_{jt}$, and the basic fossil fuels, BFS_{jt}.

$$BFS_{jt} = A_j^{BFS}\left[\beta_j^{BFS}CRD_{jt}^{-\rho_j^{BFS}} + \left(1-\beta_j^{BFS}\right)SLD_{jt}^{-\rho_j^{BFS}}\right]^{\left(\rho_j^{BFS}\right)^{-1}} \tag{5}$$

$$SLD_{jt} = A_j^{SLD}\left[\beta_j^{SLD}COAL_{jt}^{-\rho_j^{SLD}} + \left(1-\beta_j^{SLD}\right)OSLD_{jt}^{-\rho_j^{SLD}}\right]^{\left(\rho_j^{SLD}\right)^{-1}} \tag{6}$$

Similarly, equation (5) shows that the composite basic fossil fuels, BFS_{jt}, is a function of Crude Oil, CRD_{jt}, and Solid fossil fuels, SLD_{jt}. While equation (6) describes the composite solid fossil fuels as a direct composite function of Coal, $COAL_{jt}$ and Other Solid Fuels, $OSLD_{jt}$.

$$CE_{jt} = \left(1-CER_{jt}\right)\sum_i \varnothing_j EN_{ijt} \tag{7}$$

$$CEI_{jt} = \frac{CE_{jt}}{P_{jt}^{VA}VA_{jt}} \tag{8}$$

$$CE_t = \sum_j CE_{jt} \tag{9}$$

Equation (7) defines the industrial-level carbon emission, CE_{jt}, as a function of the Carbon Efficiency Rate for industry j at time t, CER_{jt}, which is also known as the Carbon Abatement Rate, the carbon factor coefficient for each industry j, $\varnothing_j$, and the intermediate input demand for energy product i by sector j at time t, EN_{ijt}. The dynamic evolution of the industrial Carbon Emission Intensity, CEI_{jt}, and aggregate level of Carbon Emission, CE_t, for the economy is captured in equations (8) and (9).

$$CT_{ijt} = \varnothing_j EN_{ijt}P_{jt}^{EN} \tag{10}$$

$$ECT_{jt} = \sum_i \varnothing_j CT_{ijt}EN_{ijt} \tag{11}$$

$$ETS_{jt} = P_t^{TS}\left[CE_{jt} - \left(\left[1-CER_{jt}\right]\gamma Q_{jt}\frac{CE_{j(t-1)}}{Q_{j(t-1)}}\right)\right] \tag{12}$$

Following a value-added scheme, the Carbon Tax rate, CT_{ijt}, of industry j at time t for energy product i is described in equation (10) using the emissions coefficient of industry j, $\varnothing_j$, the intermediate demand for energy products, EN_{ijt}, and its prices P_{jt}^{EN}. Equation (11) shows the application of the carbon tax rate on the intermediate energy product used by the industries or sectors, in the form of the Energy Carbon Tax for industry j at time t, ECT_{jt}. In the carbon emission trading market, industries are allowed to participate in this market which is based on the cap-and-trade system. As such, the cost of the Emission Trading Scheme (ETS) for other industries is zero when they do not participate in the carbon emission cap-and-trade market. For those industries that participate in this carbon trading market, their ETS_{jt} cost is defined as Equation (12) as a function of the carbon trading scheme price, P_t^{TS}, present and past period industrial carbon emission, CE_{jt} *and* $CE_{j(t-1)}$, the allowance rate, γ, carbon abatement rate, CER_{jt}, and past and present period industrial output, Q_{jt} *and* $Q_{j(t-1)}$. In other words, the carbon ETS cost is defined on the excess of an industry's carbon emission over the allowed. This suggests that the ETS cost can also apply to energy products-producing industries as much as the ECT. Nonetheless, the energy-producing sectors or industries are at the intersection of these two schemes, ETS and ECT, given that they also use or demand a proportion of their outputs as inputs for producing their outputs.

$$CV_{at} = \left(\frac{\sqrt[2]{\sum_i C_{iat}^{I}} - \sqrt[2]{\sum_i C_{iat}^{0}}}{\sqrt[2]{\sum_i C_{iat}^{I}}}\right)Y_{at}^{I} \tag{13}$$

$$EV_{at} = \left(\frac{\sqrt[2]{\sum_i C_{iat}^{I}} - \sqrt[2]{\sum_i C_{iat}^{0}}}{\sqrt[2]{\sum_i C_{iat}^{0}}}\right)Y_{at}^{0} \tag{14}$$

Comparative Variation for domestic agent a at time t, CV_{at}, and the Equivalent Variation for domestic agent a at time t, EV_{at}, are defined on the policy level concave utility of the domestic agent, a, on the aggregate consumption of good i at time t, C_{iat}^{I}, relative to the concave utility of the benchmark consumption, C_{iat}^{0}. Similarly, Y_{at}^{I} is the domestic agent a's income due to the policy change while the benchmark income is Y_{at}^{0}. The specific definitions of the CV_{at} and EV_{at} follow equations (13) and (14). These variations are used to measure the domestic agents' welfare improvement as a result of the policy change relative to not having the policy change, in monetary values. The complete picture of the dynamic EEICGE (V.4.0) model is captured in Fig. 1.

3.2. Energy security scenario design development

Being the most populous African nation and coupled with its rapid population growth, Nigeria is faced with increasing resource demand, particularly, on energy products. This leads to the development of the Nigerian Renewable Energy Master Plan (REMP). This policy is geared towards substantially improving the renewable energy supply contribution to total energy generation from 13% in 2015 to 23% by 2025 and to 36% by 2030.[1] Fiscal and market incentives to support the REMP implementation and deployment were carried out. The REMP policy is targeted at improving the consumption and use of renewable energies to

[1] See the more details in the article by the International Energy Agency (IEA), https://www.iea.org/policies/4974-nigeria-renewable-energy-master-plan.

10% of the total energy consumption by 2025. To achieve this, substantial investments are required, such as hydro capacity installations, solar PV installations, biomass power plants, grid integrations, wind capacities, etc. by 2025. As part of the master plan, other policies like the National Renewable Energy and Energy Efficiency Policy (NREEP), Feed-in-Tariffs (FiTs), Rural Electrification Policy (REP), Tax Incentive Policies (TIP), etc. were developed towards achieving the goal of a 10% increased consumption of renewable energies, relative to the total energy consumption in Nigeria.

Increasing renewable energy consumption in Nigeria suggests the availabilities and supply of renewable energies that are capable of meeting the 10% targetted increase in renewable energy consumption. As such, this study examines a 10% additional increased investment in the level of renewable energy mix in Nigeria to meet the targetted 10% increase in renewable energy consumption. By definition, energy security deals with the affordability and availability of energy within the economy. Particularly, the target of this study is the improvement of the availability and affordability of clean and/or renewable energies for the African economies. As such, a variety of policy designs that are targeted at improving the state of energy security in an African economy are explored. Generally, there are three (3) policy designs implemented in this study. These are the One-off Capital Investment in the Renewable Energy Mix (CIREMOO), the Five-year Capital Investment in the Renewable Energy Mix (CIREM5Y), and the Gradual Incremental Capital Investment in the Renewable Energy Mix (CIREMGI).

For CIREMOO, CIREM5Y, and CIREMGI scenarios, a 10% additional investment in the level of the renewable energy mix in an African economy is implemented. However, the process of implementing this 10% additional capital investment differs across the designs or plans. In CIREMOO, the 10% capital investment is implemented once and at the beginning of the policy year, 2024. However, the 10% additional capital investment is spread out or distributed for five (5) years under the CIREM5Y design. That is, there is a 2% additional capital investment in renewable energy mix from 2024 to 2028. Conversely, the CIREMGI design gradually increases the capital investment by 1% for each successive year in four (4) years, 2024–2027. That is, for every current year, the renewable energy mix capital investment is a percentage increase on that of the previous year.

It is important to state that this study practically assumes that increased investment in Africa's renewable energy mix is undeniably a welcomed target or strategy towards achieving clean or renewable energy security in Africa. In particular, the developed policy designs (CIREMOO, CIREM5Y, and CIREMGI) are mainly targeting the mode of implementation that will achieve the best energy security results for the entire economy.

The data set used in this study is the updated 2019 Nigerian Social Accounting Matrix (SAM), adapted from Okorie and Wesseh (2024) and Okorie and Lin (2024). This SAM captures twenty-two (22) sectors of the Nigerian economy, disaggregated economic agents and factor inputs. The population year-on-year growth parameter is set to 2.41%, a 10% depreciation rate parameter and an 18% interest rate.[2] The value-added elasticity parameter follows the estimation of Okorie (2021) for Nigeria while the rest of the elasticity parameters follow Okorie and Wesseh (2024). Other model parameters are calibrated from the Nigerian SAM data.

4. Results and discussions

4.1. Economic welfare analysis

The comparative statics results are discussed under different subsections. Economic welfare presents a few key indicators that measure and capture the welfare level of an economy but at aggregate and individual levels. Fig. 2 shows the comparative static results of the real Gross Domestic Output (real GDP) for all the designed scenarios. For the next decade, all the scenarios show improvements in the output level due to the capital investment in renewable energy mix. Moreover, there are few noteworthy differences among these three (3) energy security paths. Firstly, the one-off 10% increase in renewable energy mix capital (CIREMOO) shows a relatively higher growth in real GDP right from the starting period until 2032. This suggests that this strategy path boosts economic growth rapidly relative to the other scenarios paths. Secondly, the five-year (CIREM5Y) and the gradual incremental (CIREMGI) paths show similar growth patterns in the near future. However, the economic output growth of the CIREMGI design outweighs that of CIREM5Y after 2028 and outweighs CIREMOO after 2032. Thirdly, the CIREMGI output growth shows a sustainable and relatively smooth transition till 2033. Lastly, the CIREM5Y exhibits similar behaviour but substantially lower. Conversely, the CIREMOO design peaks in 2031 and declines after 2032. Based on these findings. The CIREMGI path to energy security in Africa is preferred given the sustained and smooth improvements in the aggregate level of the economic output, which suggests economic growth.

The results in Fig. 1 capture the economic welfare of the entire economy on an aggregate level. The Equivalent Variation (EV) and Comparative Variation (CV) are used to capture the welfare of the individual domestic agents. Table 2 shows the EV (approximately equal to the CV) results due to the three policy design paths. A positive EV confirms welfare improvement while negative values show welfare deterioration. Typically and by definition, these EV results represent the extra amount of money, in Nigerian Naira (₦), needed by the represented economic agents to maintain the post-increased renewable energy mix investment utility level at current prices. That is to say; without the increased renewable energy mix investment policy plan, the represented Nigerian economic agents would require respective income changes, up to the values in Table 2.

Based on the results in Table 2, there are near future welfare sacrifices by all the disaggregated to achieve the desired energy security levels. These sacrifices are relatively short-lived and do not last forever. This is confirmed by the CIREMOO design which shows a six (6) years welfare sacrifice for the desired energy security due to the increased investment in renewable energy mix. While this is not the case for CIREM5Y and CIREMGI, they show a decline in the welfare loss after the five (5) and four (4) years investment periods. Therefore, it is expected that the disaggregated household agent's welfare level will improve after 2033. CIREMGI design shows a continuous welfare loss due to the annual increase in capital investment in the renewable energy mix. These results are due to the overall increases in the consumer price index (CPI), see Table 3, due to the increased capital investment in the renewable energy mix and the fall in real income (both labour and capital income) resulting in decreased real consumption of goods and services. Generally, these welfare losses are short-lived with a concave pattern; increasing at a decreasing rate. For instance, the CIREMOO path shows welfare loss for 6 years into the future and becomes positive afterwards. The CIREM5Y and CIREMGI scenarios also show declining welfare loss and will eventually become positive just like the CIREMOO scenario. This is in line with Solow's model predictions for an economy with a low steady-state effective capital that transitions to their golden rule steady-state effective capital. For such economies, the present and near future consumptions are sacrificed for higher future consumption as they transition. This finding further clarifies that the level of renewable energy capital mix in Africa, using Nigeria as a case study is

[2] See https://www.macrotrends.net/countries/NGA/nigeria/population-growth-rate for the choice of population growth. See https://taxsummaries.pwc.com/nigeria/corporate/deductions for the depreciation rate and for the interest rate, see https://www.reuters.com/markets/rates-bonds/nigerias-central-bank-raises-benchmark-lending-rate-18-2023-03-21 and https://www.cbn.gov.ng/rates/mnymktind.asp.

substantially below the golden rule level of capital which achieves the highest possible welfare, consumption and leisure. Comparing the three path designs, CIREMGI is preferred given that it results in the least welfare loss as the economy transitions through the energy security path. On the other hand, the welfare loss of the households implies welfare gain for the government who has more consumption due to the increased government expenditure, howbeit, an increased capital expenditure.

Table 3 shows the aggregate price level of goods and services in the economy due to the increased capital investment. The basic CPI and the chain-weighted CPI measures are used to capture the aggregate price level. The chain-weighted CPI tends to capture the dynamic changes in the consumers' spending patterns to provide a better picture of the cost of living based on the goods and services consumed at each time. Generally, capital investment policies result in overall inflation most of the time. This inflation challenge of increased renewable energy investments is also supported by the findings of Zhang and Guo (2024).

4.2. Decarbonization and net-zero analysis

Fig. 3 compares the carbon abatement comparative statics for the designed scenarios. Particularly, the one-off path results in higher carbon abatement in the immediate future, however, it eventually reduces to positive carbon emission growth before the end of the decade. On the contrary, the five-year plan and the gradual incremental plan show continuous and sustained carbon abatement all through the decade. Comparatively, the gradual increment gives an increasing year-on-year growth in carbon abatement to achieve decarbonization in the overall economy.

In the EEICGE model, fossil fuels are decomposed or disaggregated into coal, other solids, crude and refined oil. The results in Fig. 4 confirm that an increased capital investment in renewable energy-mix will adversely affect the production of fossil energies. This is intuitive since the investment in renewable energy mix capital is expected to increase the production of renewable energy mix which are close substitutes to fossil fuels. The advantages of renewable energies over fossil energies can not be overstated. As such, the increased output of renewable energy mix will be accompanied by an increased demand. This implies a fall in the demand for fossil fuels and then, a decrease in the production of fossil energies. This is expected given the positive cross-elasticity that exists between fossil fuels and renewable energy mix. Suggesting that the renewable energy mix is relatively cheaper than fossil energy inputs, which is consistent with the comparative static results of the EEICGE model. Relatively, the gradual incremental strategy produces a continuous and sustainable decrease in the production of fossil outputs.

The information in Table 4 further buttresses the results in Fig. 3. The consumption of fossil fuel energies as intermediate inputs of production gives rise to industrial carbon emissions. This does not imply that the consumption of renewable energies does not emit carbon. However, the carbons emitted from the consumption of renewable energies are significantly minimal and trivial. Table 4 shows that generally, a capital investment in a renewable energy mix decreases the use and consumption of fossil fuels in production activities while increasing that of renewable energy mix, thereby, leading to decarbonization and net-zero. These results further give light to the preceding results in Fig. 4. The fall in the demand for fossil fuels, for production purposes, relative to renewable energies justifies and informs the fall in the production of fossil fuel outputs. These results are intuitive given that the renewable energy mix are input substitute for fossil fuel. As such, an increased renewable energy mix capital investment would result in an increased renewable energy mix, thereby, increasing the availability and access of the renewable energy mix. This, in turn, would lead to the substitution of fossil fuels with renewable energy mix alternatives based on the industrial marginal rate of technical substitution of renewable energy mix for fossil fuels.

Table 5 shows carbon intensity comparative statics. The negative carbon intensity denotes a faster decline in carbon emission relative to the rise in productivity (value added). More details that lead to the results in Table 5 are captured in Figs. 2 and 3. This is a desired outcome of an increased capital investment in renewable energy mix and thus, promotes decarbonization and net-zero in the economy. The negative sign of the carbon intensity is explained by both the decreases in carbon emission, which is directly related to carbon intensity, and the increases in real output, which is indirectly related to carbon intensity. However, for the CIREMOO scenario, the carbon intensity became positive after 2030 due to the fact that the increase in carbon emission outweighed the increases in the real output level. By implication, the one-off negative carbon intensity is higher for the immediate and recent future but fizzles out before the end of the decade. Conversely, the five years and the gradual incremental policy plans produce a sustained decarbonization and net zero for the economy. Generally, the results discussed in this subsection are mainly for and promote decarbonization, carbon abatement, and net zero.

4.3. Renewable energy security analysis

This section is dedicated to discussing the (renewable) energy security results, that is, the affordability and availability of (renewable) energies. Table 6 presents the comparative static results of renewable energy prices relative to fossil fuels due to the increased renewable energy capital investment. Generally, there is a fall in the overall prices of both renewable energy mix and fossil fuels. Thereby leading to increased affordability of energy due to the increased capital investment in renewable energy mix policy designs. However, the fall in the renewable energy mix is relatively larger than the fall in fossil fuel prices. This suggests that the demand for renewable energy mix would increase based on the relationship between prices and quantity demanded. This will also be the case for fossil fuel but the demand for the renewable energy mix outweighs that of the fossil fuels. This expectation is confirmed by the results in Table 4, which shows increased quantity demanded of renewable energy mix outweighs that of fossil fuel.

Next, the availability of the renewable energy mix due to the capital investment policy design is examined. The results in Table 7 show the output growth or comparative statics for the renewable energy mix and fossil fuels due to the policy designs. The results show that the renewable energy mix output increases while that of fossil fuel decreases for most of the periods. Thereby improving the availability of renewable energy mix. These comparative statics are highly intuitive; renewable energy-mix are alternatives to fossil fuels, as such, the higher fall in the price of renewable energy-mix makes them appealing, in addition to their advantages over fossil fuels, and increases their demand. This implies that lesser quantities of fossil fuels will be demanded relative to the past quantity demanded since the renewable energy mix alternatives are employed. Thereby, reducing the production or output of fossil fuel energies despite its fall in price as shown in Table 6.

Particularly, the renewable energy mix demand results from the domestic agents of the economy is shown in Table 8. These comparative results generally show a positive change in the demand for renewable energy mix by the domestic agents while that of fossil fuel shows a negative change in quantity demanded most of the time. A greater proportion of this increased demand for renewable energy mix is attributed to the firms or businesses. This suggests more carbon abatement, decarbonization of the industries and net zero. Another striking result or finding is that the comparative statics for the increase in demand for renewable energy mix outweighs the comparative statics for the increase in the renewable energy mix output (see Table 7). This suggests a potential and non-trivial market for renewable energies in Africa. This is promising and justifies the continued development and evolution of the renewable energy sector in Africa.

As a robustness check, this study further applies two (2) other policy options, in addition to the 10% capital investment increase in the renewable energy sector. These are a 10% increase in renewable energy subsidy (Guo et al., 2020) and a 10% decrease in renewable energy capital tax (Kancs, 2007; Pradhan and Ghosh, 2022; Yeo and Oh, 2023). The findings are not significantly different from the main results presented earlier. This is largely because the renewable energy mix sector of the Nigerian economy is not well developed to the extent an increase in renewable energy subsidy and/or a decrease in the capital tax of the renewable energy sector could result in significant comparative statics in the Nigerian economy. Generally, our results and findings agree with that of Adedeji et al. (2024) and Ofosu-Peasah et al. (2024, 2021) that for the African economies, the availability and affordability of (renewable) energy products and sources are priority factors. This suggests that resolving the issues of energy product availability and affordability, as shown in this study, is taking the right steps toward solving the energy security challenges in Africa. These are just the first steps as more efforts are required to curb the distortions, security, sustainability, and reliability of the supplied energy products in Africa. Similarly, our results and findings confirm that of Xu et al. (2024) and Lin and Wang (2024) on the investment effects of the renewable energy sector in developing the level of renewable energies in an economy.

5. Conclusions

Amongst a few options to boost the level of renewable energy in Africa, capital investments stand tall. This article investigates different energy security paths for capital investment in renewable energy mix in Nigeria, an African country. The findings show that lumpsum and one-off investments improve the level of energy security in the near or recent future while the gradual incremental investment plan smoothens the improved energy security into the far future. Generally, capital investments in the renewable energy sector prove to be a noteworthy approach towards increased energy security in Africa, using Nigeria as a case study. This study contributes to the existing body of literature on improving (renewable) energy security of developing economies by first taking a holistic approach that investigates the overall implications of renewable energy investment pathways and how they affect all the different aspects of an economy. Secondly, for economies that are endowed with abundant fossil fuel energy resources, improving their renewable energy requires both incentives and active participation of the various businesses in consciously taking actions to reduce carbon emissions through their production activities. Therefore, this study further contributes to the body of existing studies by developing a model that dynamically allows all the production or real sectors to decide the level of fossil fuel or renewable energy intermediate products to use in their production processes. This dynamic substitutability of the intermediate energy product during the production processes will improve the involvement of the sectors to simultaneously achieve a green economy and improve the level of energy security in the economy. Practical policy implications of the findings of this study may include, but are not limited to the following;

1. To boost the level of (renewable) energy security in Africa, increased capital investment in the (renewable) energy sector is highly effective and productive relative to other approaches like (renewable) energy subsidies, (renewable) energy capital tax incentives, etc. These other approaches become productive in well-developed (renewable) energy markets against evolving and developing markets. This is because this study shows that capital investments in the renewable energy sector show substantial improvement in the energy security level in the African economy relative to other alternative approaches.
2. Based on the results, If the fund or capital is available, a lump-sum one of capital investment in the renewable energy sector depicts an aggressive move into elevating energy security in Africa which has been shown to lead to an improved immediate future level of energy security through reducing the price of renewable energies and increasing its outputs. This is reinforced by the CIREMOO pathway results and might be the immediate solution to the inadequate energy security level in these economies.
3. Alternatively, if the lump sum capital investment is not available, a gradual incremental investment path is recommended since it is comparable to a fixed proportion capital investment. Both paths spread out the energy security benefit into the far future. In an actual sense, the choice of a path depends on the availability of the capital. This is supported by the CIREMGI energy security pathway results and findings. It proves to be relatively cost-effective for developing economies, compared to the other energy security pathways proposed in this study.
4. Making these evidence or result-based policies are necessary conditions and not sufficient. The implementation of these policies is vital. These implementations guarantee the actualization of the desired and discussed results and findings. This is largely because the results and findings of this study assume that the policies or designed scenarios are implemented in the economy to produce these results. As such, it is vital to fully implement these energy security policy pathways to achieve the results shown in this study.
5. It is equally important to point out that only capital investments from the government might not be enough to engineer the desired renewable energy security outcomes. A pool of capital from both the government and private entities through external savings should be encouraged to foster rapid development in Africa's renewable energy sector as shown in the study results and findings.
6. Besides, the increased capital investment in the renewable energy sector should and ought to be accompanied by other policies that can counteract the adverse effects of the capital investment policies such as the decreases in welfare measured using the equivalent and comparative variations, as shown by the study results. For instance, the government can provide incentives to households to encourage their consumption amidst the increases in the aggregate price level of goods and services.

Generally, the key study limitation encountered in this study is in the area of the dataset to feed the proposed dynamic computable general equilibrium model. This dataset is called the SAM, which shows the flow of resources from among the agents and sectors of an open (or closed) economy. This is especially the case for most African economies given the unavailability of existing SAM or even an IO (Input-Output) table. This challenge was overcome by using the updated 2019 Nigerian SAM that was prepared by a group of macroeconomics scholars (Okorie and Lin, 2023; Okorie and Wesseh, 2024). As a suggestion for further studies, computable models should look towards modelling the substitutability of intermediate energy products statically and dynamically. This study takes the lead in doing this and scholars could invariably look into this modelling approach too as it would allow the model to better capture the renewable energy transitioning pathway for mostly developing economies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendices.

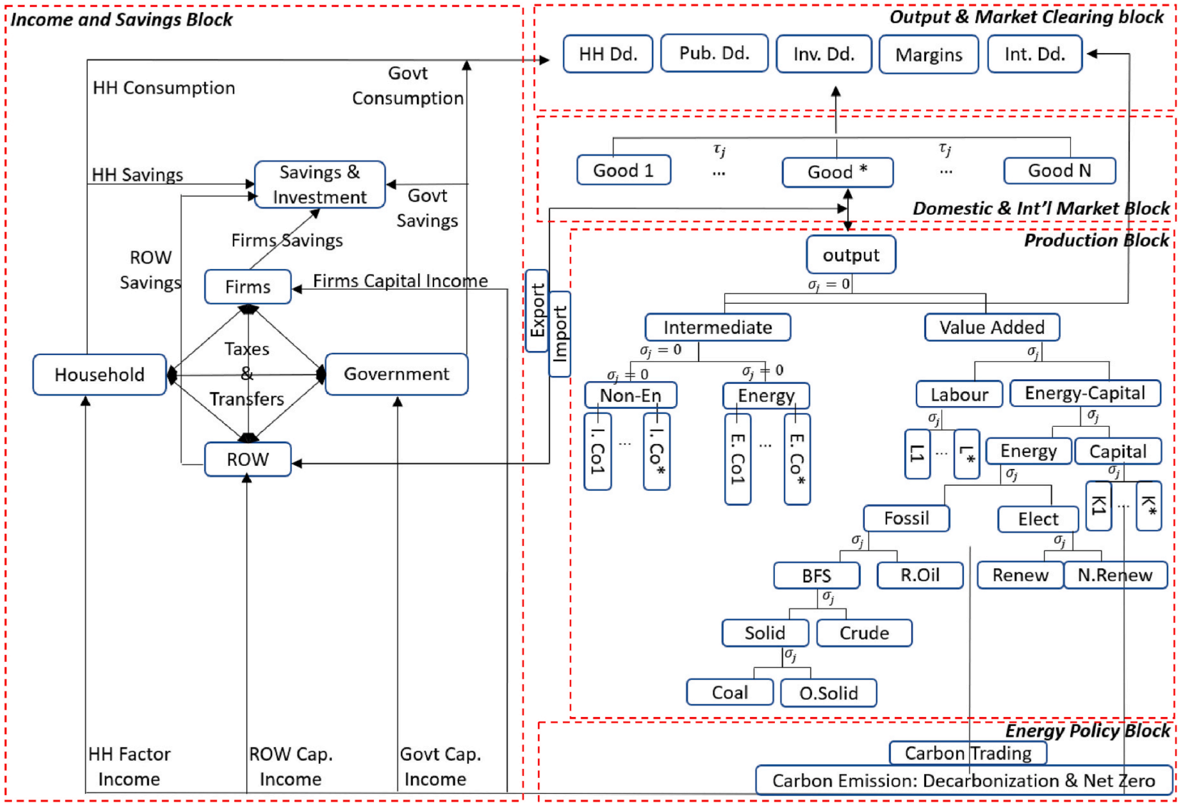

Fig. 1. EEICGE Model Schema

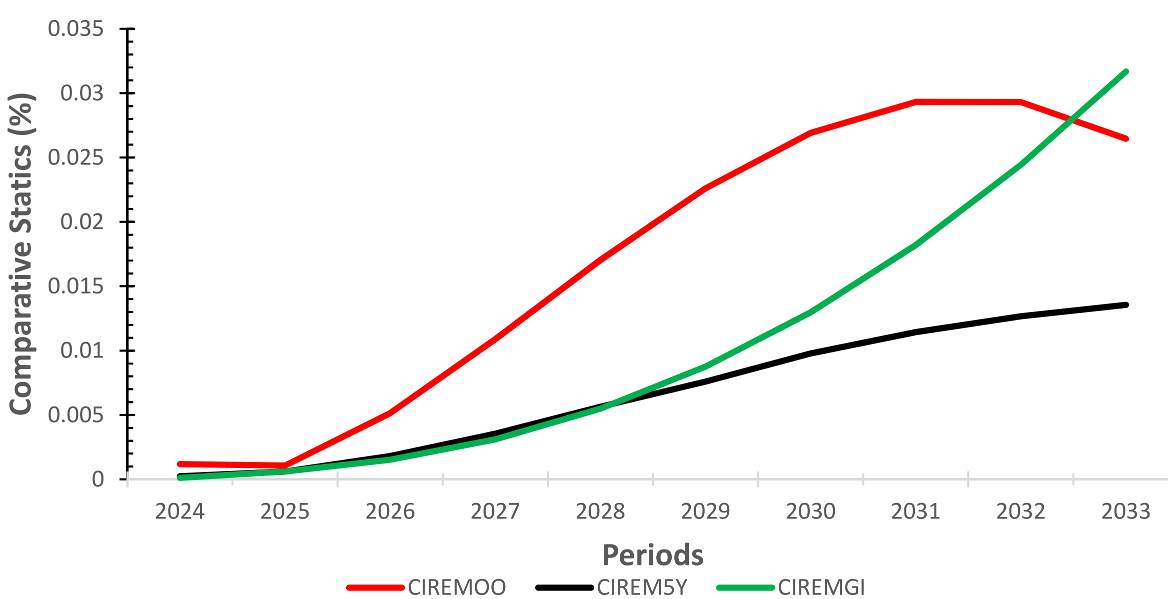

Fig. 2. Real Output Growth

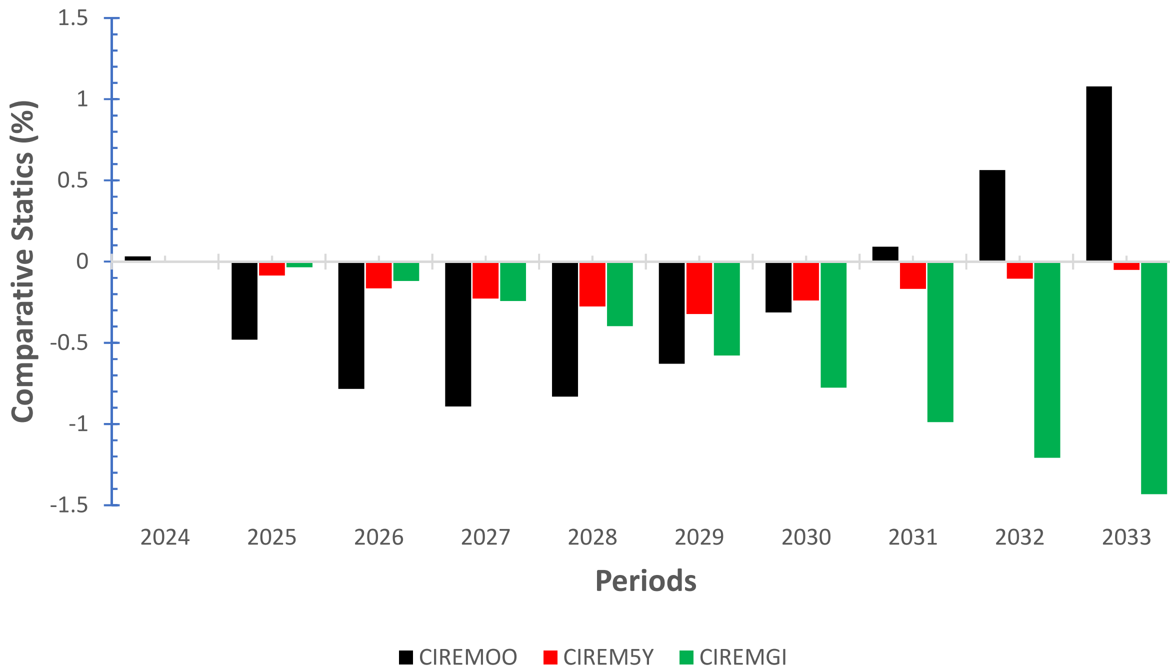

Fig. 3. Carbon Abatement

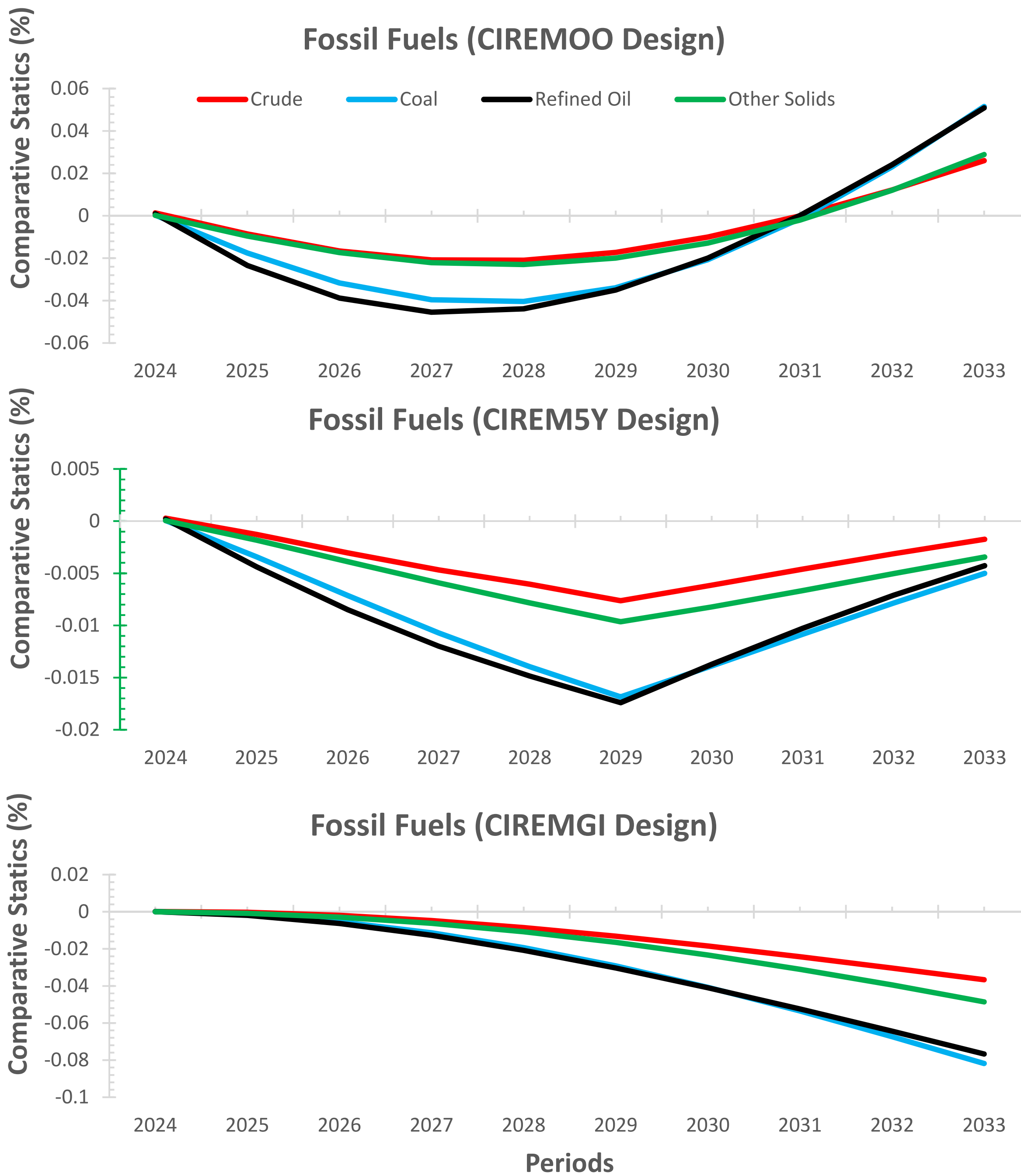

Fig. 4. Fossil Fuel Output Production

Table 1
Stylized Energy Accessibility Facts

		2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
AE	**Nigeria**	48.00	55.90	53.00	55.60	54.20	52.50	59.30	54.40	56.50	55.40	55.40
	Africa	45.27	46.24	47.41	48.35	50.53	51.54	53.87	54.65	55.82	57.22	58.23
	ROW	93.56	93.98	94.58	95.01	95.58	96.23	96.25	96.73	97.05	97.23	97.3
ACFT	**Nigeria**	1.80	2.10	2.50	3.20	4.10	5.50	7.30	9.80	12.90	16.35	19.80
	Africa	26.68	27.06	27.54	28.00	28.5	29.01	29.56	30.11	30.71	31.27	31.87
	ROW	78.9	79.4	79.87	80.32	80.78	81.18	81.58	81.98	82.33	82.66	82.96

AE is Access to Electricity, ACFT is Access to Clean Fuels and Technologies, ROW is the Rest of the World.

Table 2
Equivalent and Comparative Variations

		2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
CIREMOO	HRP	0.047	−2.399	−3.417	−3.543	−3.049	−2.100	−0.806	0.751	2.506	4.404
	HUP	0.032	−1.846	−2.735	−2.931	−2.601	−1.860	−0.793	0.531	2.054	3.727
	HRR	0.082	−1.622	−2.488	−2.730	−2.476	−1.817	−0.826	0.433	1.906	3.546
	HUR	0.135	−1.864	−3.215	−3.808	−3.666	−2.858	−1.474	0.396	2.664	5.250
	GVT	0.145	9.230	15.219	18.398	18.998	17.215	13.211	7.124	−0.929	−10.849
CIREM5Y	HRP	0.010	−0.465	−0.780	−0.998	−1.151	−1.275	−0.889	−0.581	−0.332	−0.130
	HUP	0.007	−0.359	−0.625	−0.822	−0.969	−1.088	−0.780	−0.526	−0.316	−0.140
	HRR	0.017	−0.299	−0.538	−0.721	−0.860	−0.994	−0.727	−0.499	−0.304	−0.138
	HUR	0.028	−0.330	−0.669	−0.964	−1.205	−1.449	−1.110	−0.797	−0.513	−0.260
	GVT	0.029	1.896	3.627	5.237	6.740	8.088	7.317	6.618	5.987	5.416
CIREMGI	HRP	0.005	−0.22	−0.603	−1.1	−1.709	−1.23	−0.852	−0.551	−0.308	−0.11
	HUP	0.003	−0.171	−0.483	−0.902	−1.424	−1.054	−0.753	−0.504	−0.298	−0.126
	HRR	0.008	−0.128	−0.398	−0.778	−1.291	−0.979	−0.715	−0.489	−0.296	−0.131
	HUR	0.014	−0.129	−0.48	−1.022	−1.803	−1.446	−1.108	−0.796	−0.513	−0.26
	GVT	0.015	0.987	2.823	5.484	8.856	8.01	7.245	6.552	5.927	5.361

HRP = Poor Rural Households. HUP = Poor Urban Households. HRR = Rich Rural Households. HUR = Rich Urban Household. GVT = Government. All the values are in billions of Nigerian Naira (₦). They represent income equivalent variations due to the scenario design shock simulations.

Table 3
Aggregate Price Level

		2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
Chain-weighted CPI	CIREMOO	−0.002	0.024	0.035	0.037	0.032	0.022	0.008	−0.008	−0.026	−0.045
	CIREM5Y	0.000	0.004	0.007	0.009	0.011	0.012	0.008	0.005	0.003	0.001
	CIREMGI	0.000	0.002	0.005	0.010	0.017	0.012	0.008	0.005	0.003	0.001
Basic CPI	CIREMOO	−0.002	0.025	0.037	0.038	0.033	0.023	0.009	−0.008	−0.026	−0.045
	CIREM5Y	0.000	0.005	0.008	0.010	0.011	0.013	0.009	0.005	0.003	0.001
	CIREMGI	0.000	0.002	0.006	0.011	0.017	0.012	0.009	0.005	0.003	0.001

Table 4
Composite Inputs Demand

		2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
Renewable Energy Mix	CIREMOO	2.446	2.840	3.042	3.067	2.940	2.691	2.347	1.931	1.459	0.948
	CIREM5Y	0.499	1.312	2.025	2.651	3.201	2.789	2.367	2.004	1.693	1.426
	CIREMGI	0.250	1.288	2.255	3.163	2.822	2.396	2.029	1.714	1.445	1.214
Fossil Fuel	CIREMOO	0.007	0.064	0.145	0.244	0.356	0.474	0.594	0.714	0.830	0.943
	CIREM5Y	0.014	0.094	0.162	0.215	0.253	0.258	0.184	0.125	0.079	0.042
	CIREMGI	0.070	0.064	0.145	0.244	0.327	0.240	0.170	0.114	0.069	0.035

Table 5
Carbon Intensity

	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
CIREMOO	0.069	−1.109	−1.841	−2.123	−1.999	−1.528	−0.773	0.203	1.344	2.598
CIREM5Y	0.014	−0.2	−0.389	−0.544	−0.664	−0.778	−0.584	−0.411	−0.26	−0.130
CIREMGI	0.007	−0.082	−0.282	−0.578	−0.989	−0.775	−0.582	−0.410	−0.260	−0.130

Table 6
Renewable Energy Mix Affordability Against Fossils

		2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
Renewable Energy Mix	CIREMOO	−0.693	−0.752	−0.776	−0.773	−0.747	−0.703	−0.643	−0.571	−0.489	−0.398
	CIREM5Y	−0.142	−0.362	−0.555	−0.725	−0.876	−0.756	−0.648	−0.554	−0.473	−0.403
	CIREMGI	−0.071	−0.360	−0.624	−0.867	−0.752	−0.646	−0.553	−0.473	−0.403	−0.343
Nonrenewable	CIREMOO	−0.007	−0.021	−0.026	−0.026	−0.023	−0.017	−0.009	0.000	0.010	0.019
	CIREM5Y	−0.001	−0.006	−0.010	−0.012	−0.015	−0.014	−0.010	−0.008	−0.005	−0.004
	CIREMGI	−0.001	−0.005	−0.009	−0.015	−0.016	−0.012	−0.009	−0.007	−0.005	−0.003

These are the local output price comparative statics for renewable and nonrenewable energies, excluding all taxes, due to the policy change designs.

Table 7
Renewable Energy Mix Availability Against Fossils

		2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
Renewable Energy Mix	CIREMOO	0.231	0.235	0.233	0.230	0.224	0.217	0.209	0.199	0.188	0.175
	CIREM5Y	0.047	0.118	0.181	0.237	0.288	0.246	0.213	0.183	0.158	0.136
	CIREMGI	0.024	0.119	0.206	0.285	0.241	0.208	0.180	0.156	0.134	0.116
Nonrenewable	CIREMOO	0.006	−0.008	−0.017	−0.021	−0.019	−0.014	−0.005	0.006	0.019	0.034
	CIREM5Y	0.001	0.000	−0.001	−0.002	−0.002	−0.004	−0.003	−0.001	0.000	0.001
	CIREMGI	0.001	0.002	0.001	−0.001	−0.007	−0.005	−0.003	−0.002	−0.001	0.001

These are the local output level comparative statics for renewable and nonrenewable energies due to the policy change designs.

Table 8
Agents' Renewable and Nonrenewable Energies Demand

		2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
Renewable Energy Mix											
CIREMOO	HRP	0.606	0.589	0.585	0.582	0.574	0.561	0.542	0.517	0.487	0.452
	HUP	0.491	0.489	0.488	0.483	0.473	0.458	0.438	0.414	0.386	0.353
	HRR	0.504	0.521	0.526	0.520	0.506	0.483	0.453	0.417	0.377	0.332
	HUR	0.465	0.487	0.492	0.485	0.468	0.444	0.413	0.377	0.337	0.293
	GVT	0.698	0.758	0.782	0.779	0.752	0.708	0.647	0.574	0.491	0.400
	FRM	14.154	15.328	15.846	15.806	15.294	14.387	13.154	11.652	9.932	8.038
CIREM5Y	HRP	0.123	0.302	0.464	0.609	0.739	0.630	0.545	0.471	0.405	0.349
	HUP	0.100	0.247	0.379	0.496	0.601	0.513	0.442	0.381	0.327	0.281
	HRR	0.102	0.257	0.394	0.515	0.623	0.533	0.458	0.393	0.337	0.288
	HUR	0.094	0.238	0.363	0.474	0.572	0.489	0.419	0.358	0.307	0.262
	GVT	0.142	0.363	0.558	0.730	0.884	0.762	0.652	0.557	0.475	0.405
	FRM	2.864	7.338	11.293	14.809	17.941	15.454	13.225	11.294	9.629	8.196
CIREMGI	HRP	0.062	0.308	0.530	0.732	0.615	0.534	0.463	0.400	0.345	0.297
	HUP	0.050	0.250	0.431	0.596	0.503	0.435	0.375	0.323	0.278	0.239
	HRR	0.051	0.259	0.447	0.619	0.527	0.453	0.389	0.334	0.286	0.245
	HUR	0.047	0.238	0.411	0.568	0.485	0.416	0.356	0.305	0.260	0.223
	GVT	0.071	0.362	0.628	0.875	0.758	0.650	0.556	0.475	0.405	0.344
	FRM	1.434	7.309	12.725	17.754	15.384	13.184	11.273	9.620	8.196	6.972
Non-Renewable Energies											
CIREMOO	HRP	0.006	−0.052	−0.073	−0.074	−0.062	−0.041	−0.015	0.016	0.050	0.086
	HUP	0.005	−0.031	−0.045	−0.048	−0.041	−0.029	−0.011	0.010	0.033	0.058
	HRR	0.006	−0.011	−0.019	−0.022	−0.020	−0.014	−0.006	0.005	0.017	0.031
	HUR	0.005	−0.002	−0.007	−0.011	−0.011	−0.009	−0.005	0.002	0.010	0.020
	GVT	0.007	0.021	0.026	0.026	0.023	0.017	0.009	0.000	−0.010	−0.019
	FRM	−1.088	−0.934	−0.831	−0.79	−0.802	−0.852	−0.927	−1.014	−1.106	−1.195
CIREM5Y	HRP	0.001	−0.009	−0.014	−0.017	−0.019	−0.022	−0.014	−0.009	−0.004	−0.001
	HUP	0.001	−0.005	−0.008	−0.010	−0.012	−0.014	−0.010	−0.006	−0.003	−0.001
	HRR	0.001	0.000	−0.001	−0.002	−0.002	−0.004	−0.003	−0.002	−0.001	0.000
	HUR	0.001	0.001	0.001	0.001	0.001	−0.001	−0.001	−0.001	0.000	0.000
	GVT	0.001	0.006	0.010	0.012	0.015	0.014	0.010	0.008	0.005	0.004
	FRM	−0.227	−0.529	−0.791	−1.026	−1.237	−1.041	−0.927	−0.822	−0.727	−0.641
CIREMGI	HRP	0.001	−0.003	−0.009	−0.018	−0.031	−0.022	−0.015	−0.009	−0.004	−0.001
	HUP	0.000	−0.001	−0.005	−0.011	−0.020	−0.014	−0.010	−0.006	−0.003	−0.001
	HRR	0.001	0.001	0.001	−0.001	−0.007	−0.005	−0.004	−0.002	−0.001	0.000
	HUR	0.001	0.002	0.002	0.002	−0.002	−0.002	−0.002	−0.001	−0.001	0.000
	GVT	0.001	0.005	0.009	0.015	0.016	0.012	0.009	0.007	0.005	0.003
	FRM	−0.114	−0.551	−0.919	−1.230	−0.979	−0.878	−0.784	−0.697	−0.618	−0.547

Data availability

Data will be made available on request.

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