FORECASTING OIL DEPLETION RATE IN THE NIGER DELTA BASIN UNDER CLIMATE CHANGE POLICY

Kaase Gbakon, Emerald Energy Institute, University of Port Harcourt, +234(0)8032309425, gbakon.kaase@eeiuniport.edu.ng
Joseph Ajienka, Professor of Petroleum Engineering, University of Port Harcourt, +234(0)7064018002, joseph.ajienka@uniport.edu.ng
Joshua Gogo, Emerald Energy Institute, University of Port Harcourt, +17806073968, jgogo@afcote.com
Omowumi Iledare, UCC Institute for Oil and Gas Studies, Cape Coast, Ghana, +234(0)8057657494, wumi.iledare@gmail.com

Abstract

Methodological approaches to oil depletion models have evolved from strict focus on engineering and geophysical drivers of reserves depletion through incorporation of economic and regulatory variables to consideration of climate change targets to ascertain sustainable levels of oil and gas extraction. Several studies of oil depletion rate for Nigeria have been conducted, but the one by Iledare & Pulsipher (2000) stand out for its incorporation of oil industry performance metrics. This paper therefore builds on Iledare & Pulsipher (2000) by acknowledging significant changes that have occurred since their seminal work with emphasis especially on climate change policy. We pursue a trinity of objectives thus: to assess Nigeria's oil industry performance indices relative to OPEC and the global industry. Secondly, to specify and estimate four alternative models of oil depletion models. Thirdly, intersect the key policy elements and assumptions of climate change with oil depletion forecast. Our results suggest that the Nigeria oil industry performance for all intents and purposes, is already fulfilling the supply side expectations required to avert the global temperature increase above 1.5 °C. The Equitable Depletion Index in Nigeria is converging toward 1.0, reserves replacement ratio has declined to 76% - lower than even the global average of 97% for 2000 – 2019, and recoverable reserves growth have averaged ~ 2% 2000 – 2019. Econometric analysis shows that continuous coordination with OPEC exhibits the largest influence on Nigeria's production when the data is observed from 1970 – 2019. Modelling over the 1970 - 1999 is unable to unambiguously reach Iledare & Pulsipher's conclusions on the backward bending supply curve phenomenon. Forecast of depletion suggest that oil production declines from 1.90 MMbbls/day in 2022 to 1.25 MMbbls/day in 2040 with attendant increase in upstream carbon emissions to 94 million tonnes of CO_2 *eq by 2040. Correspondingly carbon tax payouts by upstream players amount to \$4 billion by 2040 if the carbon tax policy is implemented at the timing and level suggested by the net zero by 2050 target. Key opportunities have been highlighted to improve carbon intensity specification of upstream oil operations in the Niger-Delta*

1. INTRODUCTION

Modeling the depletion rate of oil from oil fields is important for several reasons which include business and strategic planning, estimation of national future earnings, testing for producer behaviour, and the assessment of oil consumer alternatives. The rise of climate change imperatives, which implicates oil production and its consumption in rising levels of anthropogenic greenhouse gas (GHG) emissions has introduced a new importance to oil depletion modeling. Under climate change constraints, the purpose of oil depletion modeling is to assess how much production can be sustained, for how long and from where. For the Niger Delta basin, from where all of Nigeria's petroleum production comes, the assessment of its depletion and hence production performance has been the subject of several papers and studies (Gbakon, *et. al*., 2022; Obite, *et. al.*, 2021; Ikwan, *et. al.,* 2018; Alalade, 2016; Kingsley-Akpara, *et. al.*, 2014; Al-Bisharah, *et. al.*, 2009; Iledare & Pulsipher, 2000). In their seminal paper, Iledare & Pulsipher (2000) pursued three objectives, two of which are extended by this paper. These two objectives are the analysis of key indices of the state of petroleum resource development and exploitation in Nigeria and secondly the specification and estimation of an integrated oil depletion model to describe Nigeria's oil extraction behaviour since it joined OPEC in 1971. However, the important insights derived, and conclusions reached by Iledare & Pulsipher (2000) justifiably require reconsideration in the light of new dynamics that have emerged, key of which is the amplified call to attention of the effects of fossil fuel use on the climate and the policy shift towards deliberately cutting down fossil fuel production and utilization. Other realities that have made "land-fall" on the scene in the two decades since the paper was published include a decline in Nigeria's production since 2005, redistribution of top destination markets for Nigeria's export oil, and the sustained dependence on oil for Nigeria's earnings.

The attainment of Net Zero Emissions by 2050 has been the object of recent energy and climate change policy with oil and gas considered a major factor in reaching the target. Beck, Rashidbeigi, Roelofsen, & Speelman (2020) asserts that as of 2015, the extraction, processing and utilization of oil and gas contributed 42% of global emissions, making the case for transition away from fossil fuels to keep within the 1.5 °C limit by 2050. The transition away from conventionally produced oil to substitutes in a bid to attain net-zero is a mitigation of the economic, strategic, and environmental risks posed by climate change (Farrel and Brandt, 2006). Debate on the nexus of climate change (with the attainment of net zero as focus) and mitigation of fossil fuel use have been varied across the spectrum. Welsby, Price, Pye & Ekins (2021) estimated that approximately 60% of oil and gas, and 90% of coal must remain unextracted for there to be a 50% probability of limiting warming to 1.5 °C by 2050. This "unburnable carbon" then gives rise to the concern of how to limit global temperature rise while minimizing the fiscal impact of declining production on fossil dependent developing countries – this question is tackled in Solano-Rodríguez *et. al.*, 2021; Huxham *et. al.,* 2019; Bradley *et. al.*, 2018. An import of the climate constraints on oil production is that in the case of Africa between 21% (McGlade & Ekins, 2015) and 50% (Welsby, Price, Pye & Ekins, 2021) of Africa's oil reserves will need to remain unextracted as part of the Continent's contribution to keep temperature rise in check. However, Dvorak *et. al.* (2022), assert that even if all anthropogenic emissions were to cease abruptly in 2021, there is still enough carbon in the atmosphere to result in a 42% chance of exceeding the 1.5 °C – a likelihood that rises to 66% by 2029. The import therefore is that society is already locked-in to exceeding the 1.5 °C limit with the stark possibility that climate targets may need reassessment to a new level of 2 °C.

Furthermore, the destination markets for Nigeria's oil have changed significantly since 2000. During the 2000's Nigeria was the fifth largest oil exporter into the US, today Nigeria is no longer listed in the top 5 exporters to the US having been replaced by Columbia in the fifth spot which supplies 3% of US crude oil imports (EIA, 2022). The reasons for Nigeria's displacement are found in a combination of declining production – by 5% per annum since 2005, the increase of oil exports from Canada into the US, increase in US domestic shale production. The climate – related significance of the destination of Nigeria's crude oil export is connected to the potential for these fossil exports to come under a border carbon tax adjustment system (BCAS). The BCAS is a mechanism designed to emplace a fair price on the carbon emitted during the production of carbon intensive goods that is imported. The idea behind this policy mechanism is to encourage low carbon production in non-BCAS countries and avoid carbon leakage amongst other reasons. Although fossil fuel trade isn't captured by the BCAS, Finley & Kim (2022) in their research study for the Baker Institute submit that whatever final form the cross-border adjustments would take, it would need to apply to the fossil fuel trade to be considered comprehensive.

Under the new realities highlighted above, therefore, this paper aims to critically review and extend the analysis by Iledare & Pulsipher (2000). Consequently, three objectives are pursued as follows: First is to carry out an assessment of Nigeria oil industry performance indices relative to OPEC and the global industry since Nigeria joined OPEC. Secondly, using econometric techniques, specify and estimate oil depletion models to draw critical conclusions. The third objective is to intersect the key policy elements and assumptions of climate change with the outlook for oil production in the Niger Delta basin.

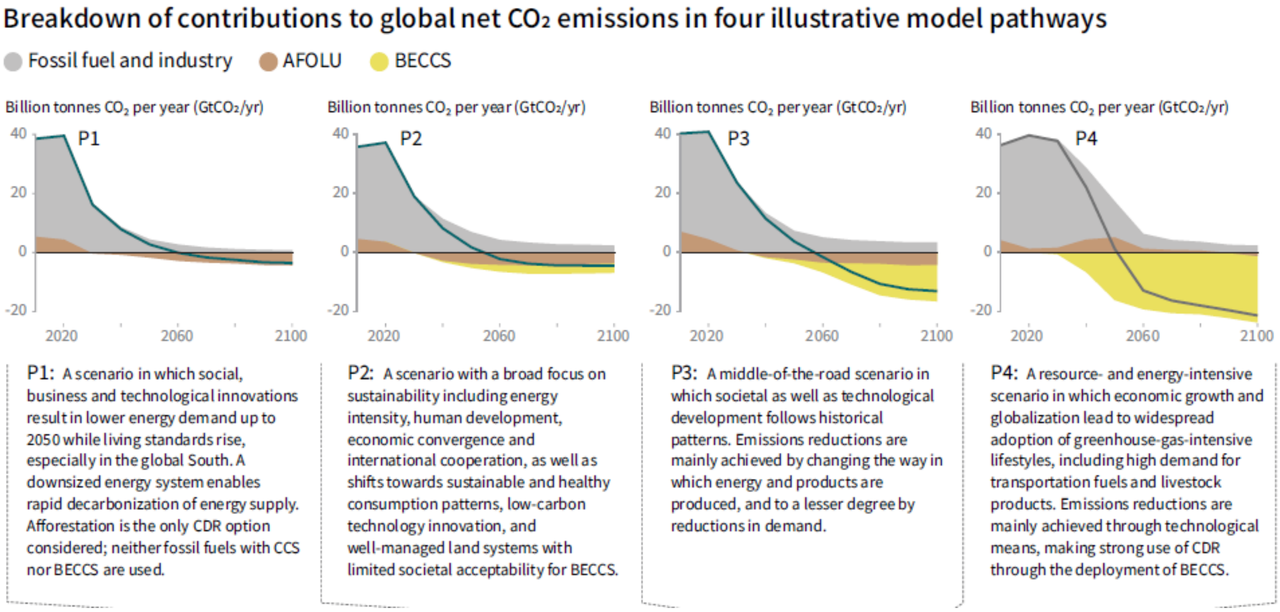
2. LITERATURE REVIEW

Iledare & Pulsipher (2000) pursue a trinity of objectives as follows:

1. The analysis of some key indicators on the state of petroleum resource development and exploitation in Nigeria.
2. Specify and estimate a Hubbert-type model to obtain a point estimate of the ultimate oil recovery for Nigeria and the maximum sustainable extraction rate.
3. Develop an integrated oil depletion model of Nigeria's oil extraction behaviour since it joined OPEC in 1971.

In meeting these objectives, important insights are derived. For example, they show that as of 1999, Nigeria's recoverable reserves had grown 9% from the 1970 level – the most aggressive relative to OPEC and the rest of the world. Furthermore, Nigeria was shown to have consistently produced oil at a level above its share of world reserves relative also to other OPEC members. Additionally, via their depletion model, they demonstrate that Nigeria's production is coordinated with the rest of OPEC, albeit in an inelastic manner. Their results also indicate that Nigeria's production tends to rise with lower crude oil prices ceteris paribus – a backward bending supply curve phenomenon that runs counter to what would be obtainable in developed economies. They also provide oil extraction rate forecasts under three cases – under the reference case, oil extraction rate declines from 2.31 MMbbls/day (2000) to 1.78 MMbbls/day (2020).

Climate change became an issue of public discourse from late 1980's (Hall, 2015) signaled by the establishment of The Intergovernmental Panel on Climate Change (IPCC) in 1988 as the leading scientific body to formulate scenarios and to understand climate change, its impacts and means of mitigation (Rosa, 2003). Against this backdrop, it is noted that Iledare & Pulsipher (2000) do not recognize the influence of climate change in their outlook even as they provide valuable insights from their analysis of Nigeria and global petroleum industry performance. According to the IPCC (2018), fossil fuels and the industry contributes the most to CO_2 emissions reductions. Thus, to limit global warming to 1.5°C (the climate policy target), fossil fuels and industry mitigation and replacement with low emissions alternatives is critical. Additionally, the IPCC show through their modelling that fossil fuels and the industry holds the key to significant CO_2 emissions reductions. Consequently, to limit global warming to 1.5°C, the mitigation of fossil use is demonstrated to be critical across all the four scenario-paths for emissions decline. This is illustrated in Figure 1.



Breakdown of contributions to global net CO_2 emissions in four illustrative model pathways

P1: A scenario in which social, business and technological innovations result in lower energy demand up to 2050 while living standards rise, especially in the global South. A downsized energy system enables rapid decarbonization of energy supply. Afforestation is the only CDR option considered; neither fossil fuels with CCS nor BECCS are used.

P2: A scenario with a broad focus on sustainability including energy intensity, human development, economic convergence and international cooperation, as well as shifts towards sustainable and healthy consumption patterns, low-carbon technology innovation, and well-managed land systems with limited societal acceptability for BECCS.

P3: A middle-of-the-road scenario in which societal as well as technological development follows historical patterns. Emissions reductions are mainly achieved by changing the way in which energy and products are produced, and to a lesser degree by reductions in demand.

P4: A resource- and energy-intensive scenario in which economic growth and globalization lead to widespread adoption of greenhouse-gas-intensive lifestyles, including high demand for transportation fuels and livestock products. Emissions reductions are mainly achieved through technological means, making strong use of CDR through the deployment of BECCS.

Figure 1: Contributions to global net CO2 emissions in four illustrative pathways to limit global warming to within 1.5°C (culled from IPCC, 2018)

The methods used for oil depletion forecasts have evolved from strictly engineering methods which considered only the physical mechanisms of oil production, through methods which incorporated economic and regulatory variables. More recent forecasts are conducted with the constraint of limiting carbon emissions to reign in global temperature rise and factor in the economics of alternatives to oil. This view is held by Brandt (2010, 2009, and 2006) who had argued that for oil depletion models to ignore the economics of substitution of conventional oil with alternatives is to forfeit the economic and environmental impacts which arise from transiting to conventional oil substitutes. In making their conventional oil supply forecasts, Welsby, Price, Pye & Ekins (2021) factored in the target of a 50% chance of limiting warming to 1.5 °C by 2050. Using a global energy systems model for their estimates, the authors concluded that approximately 60% of oil and gas, and 90% of coal must remain unextracted to keep within a 1.5 °C carbon budget. Specifically, the authors averred that, globally oil and gas production must decline by 3% per annum until 2050 for global emissions to stay within the carbon budget. For Africa, Welsby *et. al.* (2021) estimated a decline from 8.8 MMbbls/day (2020) to 3.1 MMbbls/day (2050).

To signal the seriousness of the climate change imperative, more than 3,500 US economists signed up to the Statement on Carbon Dividends[1] which advocates a carbon tax as the most cost-effective lever to reduce carbon emissions. The Statement contained other critical policy recommendations summarized as follows:

1. An annual increase in the carbon tax until emissions reductions goals are met
2. The establishment of a border carbon adjustment system to preserve U.S. competitiveness and forestall carbon leakage

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[1] Economists' Statement on Carbon Dividends (Climate Leadership Council, 2019), https://clcouncil.org/economists-statement/

3. all revenue derived from the carbon tax should be returned directly to U.S. citizens via equal lump-sum rebates.

The policy recommendation of annual increases in the carbon tax in the Statement of Carbon Dividends has found expression in the structure of the carbon tax proposed in the IEA NZE 2050 to complement the attainment of the Net Zero objective. The recommendation on the establishment of the border carbon adjustment system (BCAS) has already been adopted by the EU (European Commission, 2022) and is under discussion in the US (Finley & Kim, 2022). The policy recommendation to return carbon tax revenue to citizens is already implemented in countries like Canada and Switzerland although with questionable outcomes (Mildenberger, *et. al.,* 2022).

3. METHODS

To achieve the objectives set forth in this paper, oil production and reserves data from 1960 to 2020 is obtained from OPEC Annual Statistical Bulletins. Due to the changing membership of OPEC, production data from 1965 to 2020 for Ecuador, Indonesia and Qatar were obtained from BP statistical tables. For these same countries, reserves data from 1980 to 2020 were also obtained from BP statistical tables. Additionally, to obtain a more complete series, reserves data were obtained from "World Oil Reserves 1948 - 2001: Annual Statistics and Analysis" for Ecuador from 1973 to 1979, for Indonesia from 1962 to 1979 and for Qatar from 1961 to 1979.

It is noted that Iledare & Pulsipher (2000) had drawn on annual issues of *World Oil*, the American Petroleum Institute *Basic Petroleum Data Book*, and several issues of *Oil & Gas Journal* to aggregate the data for Nigeria, OPEC and the world. Using the data aggregated from OPEC ASB, BP statistical tables and the "World Oil Reserves", the comparative indices are reconstructed for the epochs in Iledare & Pulsipher (2000) and then extended to more contemporary period to enable commentary based on recent data.

The oil depletion model is then estimated on the following three time periods: 1970 – 1999, 2000 – 2019, and 1970 – 2019. The first time-period (1970 – 1999) is an attempt to reconstruct the oil depletion model developed by Iledare & Pulsipher (2000) which will form the basis of interrogating their conclusions. The second time-period (2000 – 2019) will enable commentary on how the estimated coefficients have changed from the first time-period. Modeling on the third period (1970 – 2019), allows a long running historical view to be admitted. By cataloguing the expected outcomes of climate change policy with specific implication for the outlook of oil prices, the model based on the 1970 – 2019 time frame is used to forecast the oil depletion pathway in the Niger Delta basin. The intersection of climate change policy and forecast oil depletion profile is further explored by the introduction of the carbon pricing mechanism and assessment of upstream oil field carbon intensity. Finally, the conclusions derived from Iledare & Pulsipher (2000) are examined to confirm if their conclusions are still valid and what it implies under the energy transition dynamics.

3.1 OPEC and Nigeria's Membership

Five countries – Islamic Republic of Iran, Iraq, Kuwait, Saudi Arabia and Venezuela – were the founding members of the Organization of the Petroleum Exporting Countries (OPEC) which was founded in Baghdad, Iraq, with the signing of an agreement in September 1960 (OPEC). Nigeria joined OPEC in 1971 and as of today, the organization has thirteen members. OPEC stated mission is to coordinate and unify the petroleum policies of its Member Countries – hence the study of Nigeria's production outlook cannot be divorced from its membership of the organization. Consequently, performance metrics for Nigeria will be compared with the remaining members of

OPEC. As shown in Figure 2, Nigeria's share of OPEC production has ranged from 4.40% (2016) to 10.73% (1985).

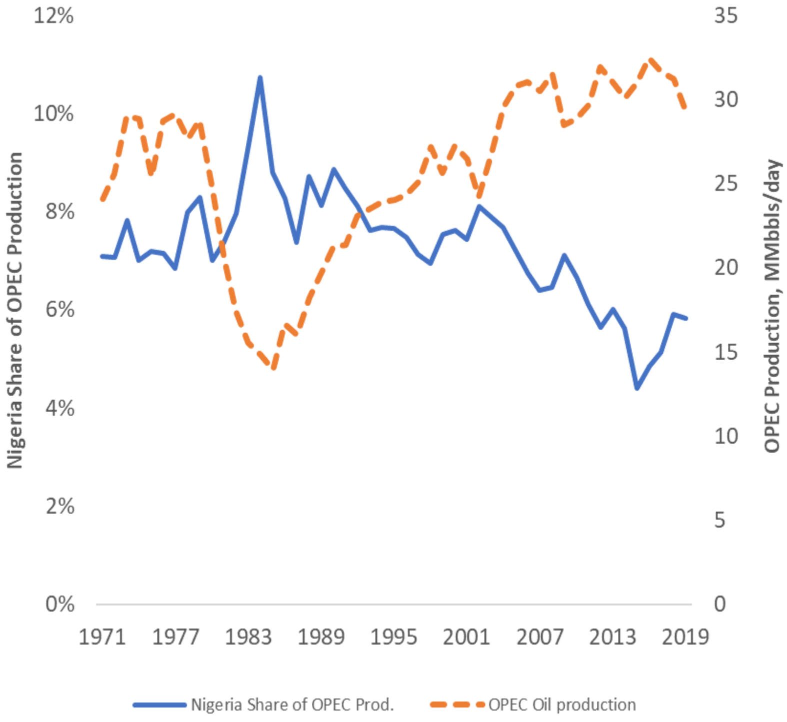

Figure 2: Nigeria's Share of OPEC Production vs OPEC Production from 1971 – 2019

Notable from the graphic is that Nigeria's share of OPEC production has declined from its peak of ~ 11% in 1985 and as of 2019, Nigeria contributed ~ 6% to OPEC production of ~ 30 MMbbls/day. Additionally, Nigeria's peak share of OPEC production coincided with OPEC's least production of 14 MMbbls/day. As OPEC production has steadily climbed from its 1985 low, Nigeria's contribution to that production has trended downwards.

3.2 Performance Indicators

Four performance indicators are utilized as the lenses through which to assess the state of petroleum industry in Nigeria, OPEC and globally. These indices are the same four used by Iledare & Pulsipher to enable a direct comparison. The indices are mathematically defined below.

Estimated Recoverable Reserves (ERR) Growth

This indicator computed on a Year-on-Year (YoY) basis is given by the equation 1

$$ERRG_t = \frac{ERR_t - ERR_{t-1}}{ERR_{t-1}} \qquad \ldots.. 1$$

Where ERR_t is the Estimated Recoverable Reserves at time t which is the sum of the Proved Reserves (PR_t) and cumulative annual production ($\sum_{i=0}^{t} Q_i$) as shown in equation 2

$$ERR_t = PR_t + \sum_{i=0}^{t} Q_i \quad \text{….. 2}$$

- $ERRG_t$ is the YoY Estimated Recoverable Reserves Growth rate at time t
- ERR_t is the Estimated Recoverable Reserves at time t
- ERR_{t-1} is the Estimated Recoverable Reserve at time $t-1$, which is the ERR one period prior.

Reserves Replacement Ratio (RRR)

This indicator computed on annually is given by the equation 3

$$RRR_t = \frac{ERR_t - ERR_{t-1}}{\sum_{i=t-1}^{t} Q_i} \quad \text{….. 3}$$

The RRR is indicative of how much of withdrawn reserves via production is replaced. A healthy industry sector is indicated by a ratio of at least 100%.

- RRR_t is the Reserves Replacement Ratio at time t
- ERR_t is the Estimated Recoverable Reserves at time t
- $\sum_{i=t-1}^{t} Q_i$ is cumulative annual production from time $t-1$ to t

Reserves Production Index (RPI)

This indicator is computed annually and is given by the equation 4

$$RPI_t = \frac{PR_t}{Q_t} \quad \text{….. 4}$$

The RPI is indicative of how much longer the proved reserves (PR_t) can last at the current production level (Q_t). The inverse of the RPI yields the depletion rate of the reserves.

Equitable Depletion Index (EDI)

This indicator is computed annually and is given by the equation 5

$$EDI_t = \frac{\left(\frac{Q_t^k}{Q_t^{WLD}}\right)}{\left(\frac{PR_t^k}{PR_t^{WLD}}\right)} \quad \text{….. 5}$$

The EDI measures the extent to which a country, region or other member of a group is producing relative to its relative reserve size. It is expected generally that a region’s share of the global production should be reasonably within its share of reserves.

Where

- Q_t^k is the production from region k at time t

- Q_t^{WLD} is the world production at time t
- PR_t^k is the proved reserves from region k at time t
- PR_t^{WLD} is the world's proved reserves at time t

The interaction between oil production and climate change policy can be explored through the following pathways:

1. The oil price outlook engendered by implementation of net zero policies. Oil price in turn drives oil production profile
2. The timing and level of a carbon tax levied on upstream oil production. This ultimately influences the amount in carbon tax pay-outs
3. Carbon intensity of upstream oil production, which tends to increase as oil depletion occurs.

These climate related elements are captured in the following sections.

Oil Price Outlook, P_t^o

According to the IEA NZE2050, the oil price path that is expected under a scenario to achieve net zero is shown in Table 1.

Table 1: Oil Price Outlook under Net Zero 2050 (IEA)

Year	Oil Price ($/bbl, RT2019)	Year	Oil Price ($/bbl, RT2019)
2022	36.84	**2032**	32.54
2024	35.98	**2034**	31.68
2026	35.12	**2036**	30.82
2028	34.26	**2038**	29.96
2030	33.40	**2040**	29.10

The profile shows a decline in oil price in real terms from $36.84/bbl (2022) to $29.10/bbl in 2040.

Carbon Price, P_t^{CO2}

Blazquez, Dale & Jefferiss (2020) argue that carbon prices can – and should – be a central feature in the adoption of renewable technologies and the use of alternative energy sources to reduce carbon emissions. This is consistent with climate change imperative.

Consequently, the carbon price level expected for Africa as per IEA NZE 2050 is modelled as a linear function of time per equation 6.

$$P_t^{CO2} = \begin{cases} 0, for\ t < T \\ m(t-T) + 3, for\ t \geq T \end{cases} \qquad \ldots 6$$

Where:

- The gradient, m, is $2.133/t CO_2eq/yr while the intercept is $3/t CO_2eq. The expectation is that carbon price will start at $3/t and increase by ~ $2/t annually
- T represents the year the carbon pricing mechanism commences. For this paper, the assumption is that it commences in 2022.

Carbon Intensity from Upstream Oil Production, $\boldsymbol{CI_{US,t}^{CO2}}$

Carbon intensity refers to the quantity of greenhouse gas emissions from upstream oil production per unit of oil produced. Carbon intensity can vary over time depending on the amount of gas flared during oil extraction, the processes required to extract the oil which itself is driven by geophysical characteristics of the reservoirs and age of the producing facilities. Although Masnadi & Brandt (2017) and Gavenas, Rosendahl, & Skjerpen (2015) demonstrate that CI_{US}^{CO2} can vary with time, and specifically increases with oil depletion, their studies are not focused on Africa/Nigeria. In the absence of Nigeria-specific studies we rely on coefficients from Abdul-Salam, Kemp & Phimister (2022) and Masnadi *et. al.* (2018) to model the profile of carbon intensity over time applicable to Nigeria. Abdul-Salam *et. al.* (2022) assumes that carbon intensity increases linearly with time. The profile for carbon intensity in Nigeria is given as:

$$CI_{US,t}^{CO2} = \alpha t + \beta \qquad \ldots 7$$

Where:

- $CI_{US,t}^{CO2}$ is the time-varying carbon intensity of upstream oil production from Nigeria expressed in tonnes of CO_2eq emitted per bbl of oil produced
- α is the annual increase in carbon intensity (estimated to be 0.0072 tonne CO_2eq/bbl/yr from Abdul-Salam *et. al.* (2022))
- β is the initial carbon intensity of upstream oil production from Nigeria (estimated 12.8g CO_2eq/MJ which is equivalent to 0.0768 tonne CO_2eq/bbl from Masnadi *et. al.* (2018))

Carbon Costs from Upstream Oil Production, $\boldsymbol{C_{PROD,t}^{CO2}}$

To determine the implied level of GHG emissions from forecast production levels and corresponding carbon costs arising therefrom we lean on the carbon intensity and carbon price models discussed above.

Relying on the time-varying carbon intensity numbers, which indicate the tonnage of CO_2eq released for every megajoule (MJ) of crude oil produced, the CO_2 equivalent emissions released from upstream oil activity in Nigeria is ascertained. Incorporating the carbon price outlook (in $ per tonne of carbon emitted), the total carbon cost associated with upstream oil production is obtained thus:

$$C_{PROD,t}^{CO2} = [P_t^{CO2}][CI_{US,t}^{CO2}][Q_{US,t}^{O}] \qquad \ldots 8$$

Where:

- $C_{PROD,t}^{CO2}$ is the cost of carbon produced from upstream operations in $MM
- P_t^{CO2} is the price of carbon expressed in $/tonne
- $CI_{US,t}^{CO2}$ is the time-varying carbon intensity of upstream oil production from Nigeria
- $Q_{US,t}^{O}$ is the quantity of upstream oil production annually expressed MMbbls

4. ANALYSIS

4.1 Climate Change Policy

Climate-change policy refers to the bundle of policy tools which may be sub-national, national, or international in scope and are intended specifically to address the issue of climate change. Climate policy come in two flavours – those designed to dampen the impact of climate change and those intended to minimize risk and exploit new opportunities (Nature, 2022). Fahn *et. al.* (2015) observes that most climate policy has been focused on the demand side of fossil fuels and posit that there is a place for supply side action from fossil producing countries in cutting emissions.

They reckon that about 2/3 of the emission reductions should come through supply side measures. This position is echoed by the IEA in their "Net Zero by 2050" report wherein the IEA submits that while continued investment in existing supply sources is required, exploration for new supply sources is not required and, no new oil fields are necessary other than projects already approved for development (IEA, 2021). Without fresh capital injection into oil investments, global supply is forecast to decline an average of 4.5% per annum from 2020 to 2050.

The Intergovernmental Panel on Climate Change (IPCC) had in their "Special Report on Global Warming of 1.5 °C" brought to sharp relief the importance of achieving global net zero CO_2 emissions by mid-century, at the latest, to avert the devastating impacts of climate change (IPCC, 2018). Consequently, the IEA expects that for Net Zero to be achieved, oil price (RT2019) declines from $37/bbl (2022) to $29/bbl (2040). This price outlook can be factored into our depletion model to forecast the Nigeria's production outlook.

As part of its climate change policy bundle, Nigeria set out a road map to achieve net zero by 2060 and passed the Climate Change Act 2021. The roadmap is designed to be implemented in phases with targets and milestones. According to the roadmap, gas flares are to be eliminated by 2030 and 95% of upstream fugitive emissions are eliminated by 2050. The Act, which objective is to provide a framework for bringing climate change actions to the fore, and to emplace a carbon budgeting system also provides a governance structure, the National Council on Climate Change. Through this Council, the principal objective of the Act will be fulfilled. Judging from the expected carbon emissions contribution arising from upstream oil production forecast, a clear implication is that carbon budgeting and the associated carbon emissions trading scheme envisioned in the law will target the upstream. Consequently, forecasts of oil production also form an input into the estimation of expected emissions and the attendant costs. It should be noted that Sec. 4(i)[2] of the Act empowers the national council to establish an appropriate price of carbon. It has long been argued that instituting a price on carbon is a way to admit and capture the cost of externalities in the process of oil extraction (Blazquez, Dale & Jefferiss, 2020). This is in adherence to the 'polluter pays' principle, which will intentionally nudge energy producers and consumers to internalize the costs of their carbon-intensive fuels and activities.

4.2 Industry Performance

Table 2 summarizes the key indices of Reserves Growth, Reserves Replacement Ratio, Equitable Depletion Index, and Reserves- Production Index. The indices are computed over the same period contained in Iledare & Pulsipher and updated to 2019.

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[2] Section 4(i) of the Climate Change Act states that "…The Council [National Council on Climate Change] shall collaborate with the Federal Inland Revenue Service to develop a mechanism for carbon tax in Nigeria."

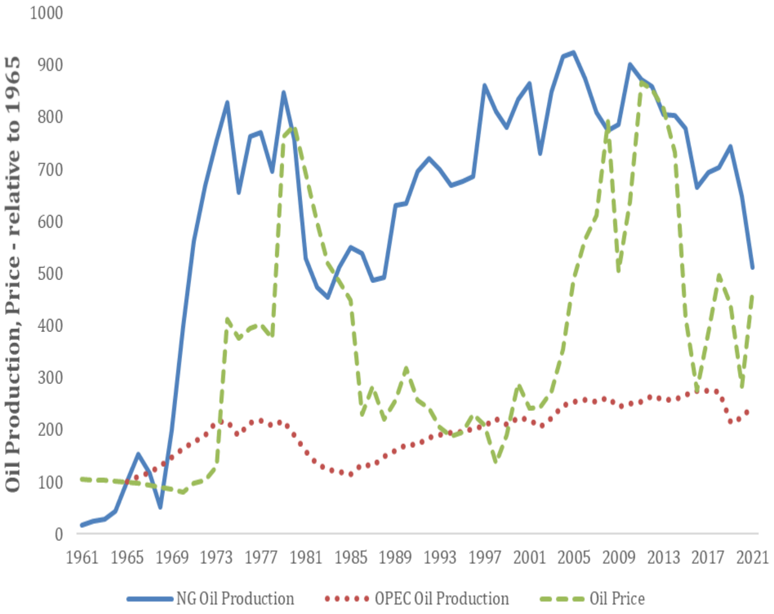

Figure 3: Profile of Nigeria & OPEC Production, Oil Price (1965 = 100)

Figure 3 summarises the trends of production and oil price from 1961 to 2021. Note that the graphic is plotted relative to the values of 1965. Comparing the production of Nigeria with that of OPEC, it is evident that Nigeria's production has grown several multiples more than OPEC's production from their respective 1965 levels. For example, by 1980, Nigeria's production was around 8-times its level in 1965, whereas OPEC production in that same year was around 2-times its 1965 level. The oil price is clearly cyclical, however trending upwards. The oil price in 2021 (measured in 2019 real terms) is around 4-times its level in 1965.

Table 2: Indicators for the State of Petroleum Development in Nigeria vs OPEC

	1970-1979	**1980-1989**	**1990-1999**	**2000-2009**	**2010-2019**	**1970-1999**	**2000-2019**	**1970 -2019**
Recoverable Reserves Appreciation Ratio								
Nigeria	18.12%	1.49%	5.45%	2.87%	0.91%	8.35%	1.89%	5.77%
OPEC	1.15%	6.20%	0.66%	2.53%	1.62%	2.67%	2.07%	2.43%
World	3.90%	4.94%	1.78%	2.55%	1.95%	3.54%	2.25%	3.03%
Recoverable Reserves Replacement Ratio								
Nigeria	195.56%	38.65%	146.43%	105.19%	47.51%	126.88%	76.35%	106.67%
OPEC	73.75%	326.90%	79.96%	158.81%	131.64%	160.20%	145.22%	154.21%
World	77.12%	143.02%	65.27%	102.84%	92.75%	95.13%	97.79%	96.20%
Equitable Depletion Index								
Nigeria	1.25	1.29	1.48	1.04	0.96	1.34	1.00	1.20
OPEC	0.70	0.47	0.51	0.54	0.54	0.56	0.54	0.55
World	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Average Production Rate (MMbbls/day)								
Nigeria	1.89	1.48	1.86	2.09	1.76	1.74	1.92	1.81
OPEC	26.77	17.99	23.45	27.67	30.92	22.74	29.30	25.36
World	54.58	55.02	60.98	68.79	73.51	56.86	71.15	62.58
Proved Reserve Production Index								
Nigeria	24.73	31.03	31.54	46.31	58.46	29.10	52.39	38.42
OPEC	43.32	87.04	90.39	88.94	103.72	73.58	96.33	82.68
World	30.50	39.42	45.85	47.74	55.51	38.59	51.63	43.80

Estimated Recoverable Reserves (ERR) Appreciation

Recoverable reserves in Nigeria grew by 18% in the 1970 – 1979 decade, which dropped to ~1.50% in the 1980 – 1989 era, and then increased to 5.45% from 1990 – 1999. Between 2000 and 2009, the recoverable reserves grew by 2.87% which further declined to 0.91% from 2010 – 2019. Overall, in the 3-decades after Nigeria joined the OPEC, recoverable reserves grew by an average of 8.35%, however, from 2000 – 2019, this metric had dropped to ~2%. This illustrates the decline in the performance of the petroleum sector.

Compared to Nigeria's stellar recoverable reserves growth rate of 8.35% in the 1970 – 1999 era, OPEC as block grew its recoverable reserves at 2.67% compared to 3.54% for global reserves growth rate. However, between 2000 – 2019, Nigeria's reserves grew by ~2% compared to OPEC's rate of 2.07% and globally a rate of 2.25% prevailed. While there has been a decline in reserves growth rate across board from the 1970 – 1999 era, there appears to be a convergence of growth rate between Nigeria, OPEC and globally.

Recoverable Reserves Replacement Ratio (RRR)

This metric is to capture how much production from reserves are replaced. Ideally, a ratio of 100% should be the target indicating that every produced barrel is at least replaced by reserves addition. For Nigeria, this ratio was 195% in the 1970 – 1979 decade, declined to ~ 40% in 1980 – 1989 and then rose to 146% in the 1990 – 1999 decade. From 1970 – 1999, Nigeria's ratio was ~127% compared to OPEC ratio of 160% and global ratio of 95%. However, from 2000 – 2019, Nigeria's ratio has come down to 76% while OPEC was above 100% at 145%. This is indicative that Nigeria in the last two decades has been depleting her reserves faster than they have been replaced.

While these ratios calculated for the historical trend do not exactly match those from Iledare & Pulsipher, they nevertheless convey the same story.

Reserves Production Ratio

The Reserves Production Ratio indicates how long proved reserves can be produced from a specified point in time assuming that extraction rate remains same. Nigeria's R-P ratio increase from ~ 25 years in the 1970 – 1979 decade to 31.5 years in the 1990 – 1999 decade. This historical R-P index implies that the average was ~ 29 years from 1970 – 1999 (which is 2.5 years higher than calculated by Iledare & Pulsipher). However, in the last two decades from 2000 – 2019, Nigeria's R-P index has averaged 52 years.

While Nigeria's R-P from 1970 – 1999 was ~ 29 years, the index for OPEC was ~ 74-years thus implying that OPEC oil reserves could last almost 2.5-times those of Nigeria at the time. from 2000 – 2019, however OPEC index is ~ 96 years which was ~ 1.8-times that of Nigeria at 52-years. The increase in Nigeria's R-P ratio is consistent with the observation that Nigeria's production has decreased faster than its decrease in reserves addition.

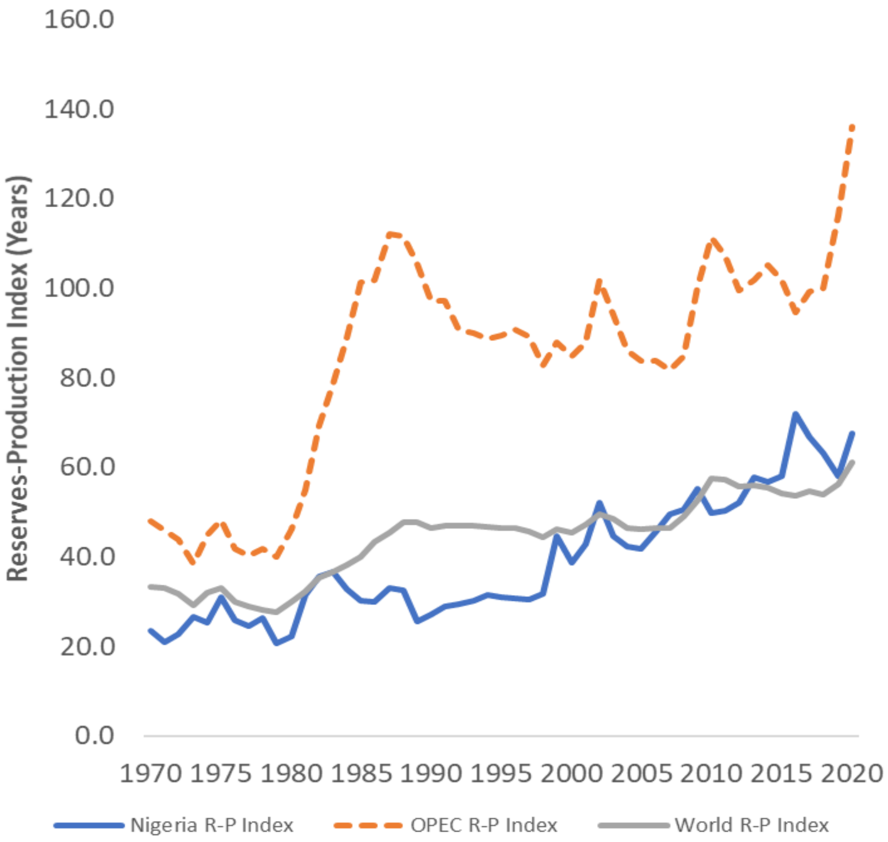

Figure 4: Profile of RPI for Nigeria, OPEC and Global

<u>Equitable Depletion Index (EDI)</u>

The EDI measures the level of proportionality between a region's relative production and its relative reserves; Ideally, EDI should equal 1. Regions with EDI more than 1 indicate "unreasonableness" in reserves extraction while an EDI lower than 1 is undesirable for long term stability of oil supply (Iledare & Pulsipher, 2000).

During the period,1970 – 1999, Nigeria's EDI was on average above 1 for each of the three decades. Specifically, from 1990 – 1999, Nigeria's EDI was 1.48 compared to OPEC value of 0.53; from 2000 – 2019, Nigeria's EDI is ~ 1. It will be noted for OPEC generally that the EDI has mostly remained between 0.50 – 0.56. Figure 5 shows the EDI trend between Nigeria and OPEC.

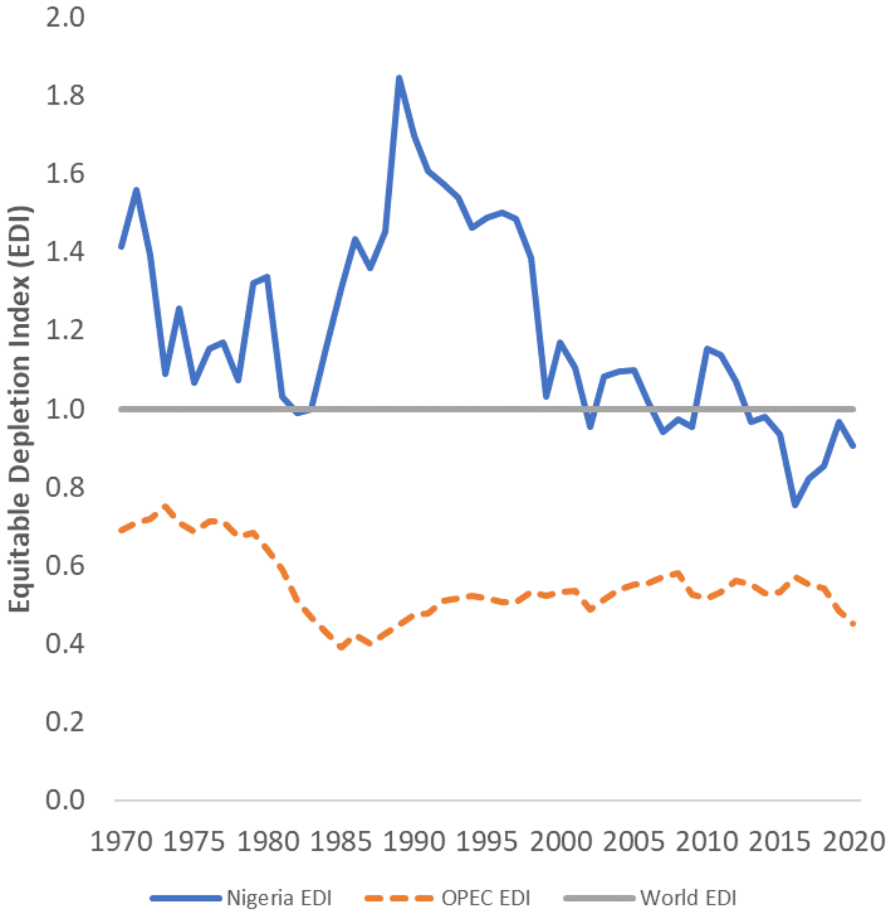

Figure 5: EDI between Nigeria, OPEC, and World

While the observation by Iledare & Pulsipher that “Nigeria has historically produced oil in excess of its share of world reserves” was correct as of 1999/2000, the updated analysis indicates that Nigeria’s EDI is converging towards unity.

4.3 Estimation of Oil Depletion Rate

The literature has emphasized the importance of including economic and regulatory variables in the estimation of future oil supply – Alalade (2016), Brandt (2006), Kemp and Kasim (2003), Iledare & Pulsipher (2000), Moroney & Berg (1999), and Al-Sahlawi (1986).

Iledare & Pulsipher specification of oil depletion model is a log – log formulation of $Q_t^{NG} = f(Q_t^{OPEC}, P_t^O, RESV_{t-1}, NPW_t, D79)$. Where, Q_t^{NG} is the oil production from Nigeria (MMbbls/day), Q_t^{OPEC} is the oil production from OPEC (MMbbls/day), and P_t^O is the real 2-period moving average price of oil in RT1982 ($/bbl), $RESV_{t-1}$ is the stock of proved reserves in Nigeria (Billion bbls) measured at the end of the previous year, NPW_t is the number of producing wells, and $D79$ is a dummy variable which is 0 before 1980 and 1 afterwards. The model incorporates geological/engineering variables ($RESV_{t-1}, NPW_t$), economic variables (P_t^O), and “regulatory” variables (Q_t^{OPEC}). Production from OPEC is considered regulatory from the perspective that production from members of OPEC is coordinated to achieve desired strategic outcomes. The observation range dummy variable captures the fact that Nigeria’s production was at its peak in 1979 (during the Iraq/Iran war) hence effectively marks a way to model depletion from Nigeria before and after the peak production within the time frame considered. Moroney & Berg (1999) specify and estimate four alternative models of annual oil production in the lower 48 states of the US using a sample period between 1950 – 1996 and find that the model of log – log functional form $Q_t = f(Q_{t-1}, RESV_{t-1}, RP_t)$, which combined one-period lag of oil reserve sizes ($RESV_{t-1}$), lagged production (Q_{t-1}), and the real oil price (RP_t) outperformed their other tested models which were based on either reserves alone or economic variables alone.

To meet one of the objectives of this paper, a modelling framework is developed to confirm the conclusions earlier reached by Iledare & Pulsipher (2000). The oil depletion model is specified and estimated in four alternative ways as described in Table 3 below.

Table 3: Model Specifications for Oil Depletion

Model #	Time Period	Model Specification
I	1970 – 1999	$\ln(Q_t^{NG}) = \beta_0 + \beta_1 \ln(RES_{t-1}) + \beta_2 \ln(P_t^o) + \beta_3 \ln(Q_t^{OPEC}) + \beta_4 D1979$
II	2000 – 2019	$\ln(Q_t^{NG}) = \beta_0 + \beta_1 \ln(RES_{t-1}) + \beta_2 \ln(P_t^o) + \beta_3 \ln(Q_t^{OPEC}) + \beta_4 D2005$
III	1970 – 2019	
IV	1970 – 2019	$\ln(Q_t^{NG}) = \beta_0 + \beta_1 \ln(RES_{t-1}) + \beta_2 \ln(P_t^o) + \beta_3 \ln(Q_t^{OPEC}) + \beta_4 D2005 + \beta_5 \ln(Q_{t-1}^{NG})$

Model I is mirrors the specification in Iledare & Pulsipher applied on the data from 1970 to 1999 except it doesn't include the number of producing wells (NPW_t) in Nigeria variable. The data on number of producing wells in Nigeria was not available for this period – the OPEC ASB captured number of producing wells for member countries between 1995 and 2015. Consequently, this variable is omitted from the analysis. The oil price used in the assessment is a 2-period moving average real term 1982 basis. Models II and III also follow after Iledare & Pulsipher, however oil price (P_t^o) used in this estimation is a 2-period moving average real term 2019 basis. Model II is applied on data for the 2000 – 2019 period, while Model III is applied on data from 1970 – 2019. Additionally, an observation range dummy variable (D2005) is included in both Models II and III to effectively to separate the production series between pre–2005 and post–2005 where 2005 was the year Nigeria recorded peak production of 2.52 MMbbls/day. Model II is estimated to observe if there have been any significant changes in the parameters from Model III. Model IV is a partial adjustment model after Moroney & Berg (1999) which is applied over the period 1970 – 2019.

The results of the estimation are presented in Table 4 in comparison with the reproduced model from Iledare & Pulsipher. All the variables in Iledare & Pulsipher are reported to be statistically significant except the number of producing wells which is retained for its structural importance to the model.

Table 4: Comparison of Model Estimation for Nigeria Production

	Iledare & Pulsipher	***Model I***	***Model II***	***Model III***	***Model IV***
Constant	−3.5898	-2.4185***	0.7866	−2.3367***	−1.5037***
Std. Error		0.3683	0.9715	0.2808	0.4288
t-Stat	−2.183	−6.5660	0.8097	−8.3230	−3.5070
$\ln(RES_{t-1})$	0.728	0.2979***	−0.5852**	0.2665***	0.1287*
Std. Error		0.0794	0.2731	0.0503	0.07323
t-Stat	2.1052	3.7510	−2.1430	5.3000	1.7570
$\ln(P_t^o)$ RT1982	−0.1854	−0.0058			
Std. Error		0.0349			
t-Stat	−1.9186	−0.1666			
$\ln(P_t^o)$ RT2019			0.2346***	0.0271	−0.0098
Std. Error			0.0509	0.0307	0.0327
t-Stat			4.6060	0.8832	−0.3011
$\ln(Q_t^{OPEC})$	0.3274	0.6836***	0.3593	0.6542***	0.5125***
Std. Error		0.1313	0.2894	0.0849	0.0988
t-Stat	1.9884	5.2040	1.2410	7.7020	5.1890
D1979	0.2208	0.0280			
Std. Error		0.0570			
t-Stat	3.0684	0.4909			
D2005			−0.1930***	−0.2167***	−0.1204**
Std. Error			0.0574	0.0452	0.0578
t-Stat			−3.3650	−4.7980	−2.0810
$\ln(NPW_t)$	0.1254				
Std. Error					
t-Stat	0.8314				
$\ln(Q_{t-1}^{NG})$					0.2757**
Std. Error					0.1113
t-Stat					2.4770
Period	**1970 - 1998**	**1970 - 1999**	**2000 - 2019**	**1970 - 2019**	**1970 - 2019**
Observations-N	22	30	20	50	50
Adj. R-Sq	0.86	0.81	0.60	0.80	0.82
D-W Statistic	2.08	1.48	1.76	1.19	2.68
F-Statistic	45.96	31.40	8.07	48.59	44.53

1% statistical significance (***), 5% statistical significance (**) and 10% statistical significance (*)

Two significant conclusions derived from Iledare & Pulsipher from their econometric analysis are that:

a. Nigeria’s production is suggestive of a backward bending supply curve phenomenon in alignment with Awokuse & Jones (1996)

b. Nigeria coordinates with a statistical significance, its production with the rest of OPEC.

Nigeria's Production as a Back-ward Bending Supply

Based on the re-assembled data, Model I like Iledare & Pulsipher shows a negative coefficient for oil price which is however statistically insignificant. Additionally, the production according to Model I exhibits a very low elasticity to oil price – around 32-times lower than reported by Iledare & Pulsipher. Furthermore, all the signs in Model I agree with Iledare & Pulsipher.

Model II exhibits a positive and statistically significant coefficient for oil price. This is the expected outcome for supply models. Al-Sahlawi's (1986) model of Saudi Arabia and pooled GCC production results in a positive coefficient for oil price.

Models III and IV both exhibit statistically insignificant coefficients for oil price, however Model III shows a positive coefficient while Model IV is a negative coefficient.

Production Alignment in Nigeria with OPEC

The coefficient of OPEC production ($\boldsymbol{Q_t^{OPEC}}$) in Model I at 0.6836 is more than 2-times the coefficient of 0.3274 in Iledare & Pulsipher. For Model II however, the coefficient of 0.3593, though statistically insignificant is closer to the coefficients obtained by Iledare & Pulsipher. Models III and IV also have positive and statistically significant coefficients. Summarily, the elasticities of Nigeria supply with that OPEC indicate that Nigeria's production is coordinated with that of OPEC. Specifically, a 1% increase in OPEC production will result in 0.65% (Model III) and 0.51% (Model IV) increase in Nigeria's production. This conclusion agrees with that of Al – Sahlawi (1986) for Saudi Arabia with respect to OPEC.

On the coefficient of the one period lag of reserves ($\boldsymbol{RES_{t-1}}$), both the Iledare & Pulsipher model and Model I are positive. Although the magnitude of the coefficient in Model I is lower than that recorded by Iledare & Pulsipher. The absence of the $\boldsymbol{NPW_t}$ variable in Model I may help explain the difference in magnitude. However, the positive sign shows that in the period between 1970 and 1999, Nigeria's production was accompanied by the reserves increase. This is consistent with the reserves replacement ratio of 127% for that period. Notice however that Model II which is estimated over the period 2000 – 2019, the coefficient of $\boldsymbol{RES_{t-1}}$ is negative. This is indicative that higher production is negatively related with one lag of reserves. This is consistent with the sub-par RRR index of 76% on average for 2000 – 2019, which shows that production was ongoing even as reserves have been in decline.

Oil Depletion Forecasts and Climate Change Implications

Model IV in Table 4 and shown in equation 9 – the partial adjustment model – is used to generate a forecast curve of oil depletion rate. Figure 6 shows the historical fit of the model and the forecast. The forecast shows that the oil production spikes up to 1.90 MMbbls/day in 2022 from where it declines to 1.25 MMbbls/day in 2040.

$$\begin{aligned}\ln(Q_t^{NG}) = -1.50 \\ &+ 0.13\ln(RES_{t-1}) - 0.01\ln(P_t^o) + 0.51\ln(Q_t^{OPEC}) \qquad \ldots 9 \\ &- 0.12D2005 + 0.28\ln(Q_{t-1}^{NG})\end{aligned}$$

The oil price outlook engendered by the net zero imperative is used in the model to generate the forecast oil depletion rate curve.

Recall that as oil wells age and production deplete, the carbon intensity of the produced oil increases. Consequently, the profile of production is used to drive the expected carbon emissions associated with oil production from the Niger Delta.

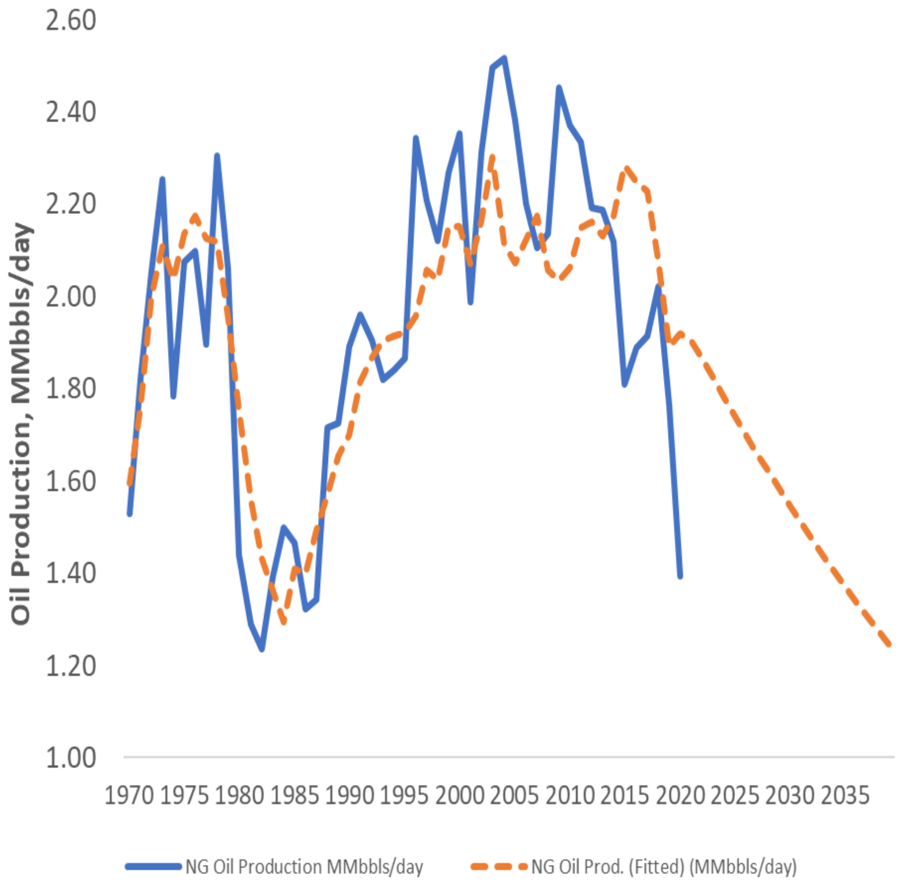

Figure 6: Historical Production Fit and Forecast

Carbon intensity from Nigeria is expected to increase from 0.08 t CO_2 eq/bbl in 2022 to 0.21 t CO_2 eq/bbl in 2040. This implies that carbon emissions increase from 53.4 MM tCO_2eq in 2022 to ~ 94 MM tCO_2eq in 2040 despite the decline in production. For this study, we have assumed that carbon pricing commences in 2022. This assumption allows commentary on what the quantum of carbon tax would possibly be even in the absence of a carbon pricing mechanism. The carbon price of $41/t of CO_2eq by 2040 translates to ~ $4 billion in carbon tax receipts.

Table 5: Profile of Carbon Implication from Forecast Depletion Rates

				RT 2019		
Year	NG Production (MMbbls/day)	Carbon Intensity (t CO_2 eq/bbl)	CO_2 emissions (MM tCO_2eq)	Carbon Price ($/t)	Upstream Carbon Tax ($MM)	Upstream Carbon Tax ($/bbl)
2022	1.90	0.08	53.40	3.00	160.19	0.23
2025	1.78	0.10	64.06	9.40	602.06	0.92
2030	1.58	0.13	77.64	20.06	1,557.70	2.70
2035	1.40	0.17	87.37	30.73	2,684.80	5.24
2040	1.25	0.21	93.97	41.39	3,889.87	8.54

The forecast of oil depletion rate allows the estimation of the carbon intensity using the model in equation 7. While the carbon intensity model adopted for this paper is adapted from other jurisdictions and is useful to give a sense of Nigeria's upstream carbon footprint, it also points to the critical need for carbon emissions studies specific to Africa and Nigeria. This is critical in the successful enforcement of the Climate Change Act and implementation of Nigeria's net zero roadmap. Furthermore, it is important to understand the impact of the carbon tax on the viability of upstream projects. By 2040, the oil depletion forecast from the Niger Delta would imply carbon tax receipts of $4 billion which represents ~ 30% (on a per barrel basis) of the $29/bbl forecast oil price. This calls for specific and deliberate policy steps on how these receipts will be judiciously deployed to the use of the State. Sec. 15(2) of the Climate Change Act provides pointers of possible deployment of such receipts.

5. CONCLUSION

Climate change policies have introduced constraints that must be placed on the supply side of fossil fuel use to avert the global temp increment of 1.5 °C – 2 °C. The historical performance of Nigeria's petroleum industry from when it joined OPEC in 1971 has been examined against the backdrop of the work done by Iledare & Pulsipher (2000) and now incorporating the climate change perspectives. Furthermore, econometric analysis has been conducted that seeks to understand the changes of Nigeria's production within the context of OPEC and energy transition dynamics. Between 1970 and 1999, Nigeria's recoverable reserves grew by 8.35% annually, however from 2000 to 2019, this average annual growth had declined to ~ 2%. On reserves replacement, since the turn of the century, Nigeria has maintained an average reserves replacement of 76% - less than 100% thus indicating that reserves are not replaced at the same rate at which it is depleted.

On the Equitable Depletion Index, Nigeria was rightly observed to have been producing above its share of reserves – between 1970 and 1999, average EDI was 1.34 compared to 0.56 for OPEC. However, from 2000 to 2019, the EDI has averaged 1 – thus implying that Nigeria's reduced production is more equitable than it has been in the past. On production, Nigeria's production has averaged 1.81 MMbbls/day since 1970. However, between 2000 and 2019, Nigeria averaged 1.92 MMbbls/day which is higher than the average of 1.74 MMbbls/day recorded between 1970 and 1999. These performance results are instructive especially in the light of pressure on supply side climate policy which will seek to reduce fossil fuel production. Given these indices, it is clear that Nigeria's production decline (see Figure 3) and slow reserves addition (averaged 2% from 2000 – 2019) is already in line with climate change and energy transition objectives.

While Iledare & Pulsipher (2000) in consonance with Awokuse & Jones (1996) are able to detect a backward bending supply curve phenomenon with regards to Nigeria oil production, this paper is unable to detect this phenomenon conclusively from the coefficient of our regressions. Granted the absence of the number of producing wells variable, modelling results over the period from 1970 – 1999 suggest a negative coefficient for oil price albeit statistically insignificant and of much smaller magnitude (> 30X smaller) than originally reported by Iledare & Pulsipher. Additionally, modelling over the 2000 – 2019 period shows a statistically significant, and positive coefficient for oil price – thus indicating that extraction rate in Nigeria moved in the same direction as oil prices over the period modelled. Additionally, even though over the period 2000 – 2019, the model (Model II) suggests that Nigeria production is coordinated with rest of the OPEC with an elasticity similar in magnitude to Iledare & Pulsipher, this coefficient is statistically insignificant. However, across all the models it is evident that there is a positive relationship between OPEC production and Nigeria's production.

Iledare & Pulispher opines that the responsiveness of Nigeria's production is significantly less than 1. The Model I which is a mirror of Iledare & Pulsipher shows an even lower responsiveness of production to changes in reserves. Over the period 2000 – 2019, Model II shows that Nigeria's production is negatively responsive to reserves changes. This is consistent with the observation that Nigeria's reserves addition has been in decline even as production has progressed. Although over the period from 1970 – 2019, Nigeria's production is shown to be positively responsive to reserves albeit with an elasticity of between 0.13 (Model IV) and 0.27 (Model III). Focusing on the period 2000 – 2019, Model II suggests that reserve changes have the largest impact on production which is similar to Iledare & Pulsipher – only that the directions of influence differ. Looking over a long-time span from 1970 – 2019, coordination with the rest of OPEC is the most significant variable in determining production (Model III and IV).

Forecast of depletion rate indicate decline in production from 1.90 MMbbls/day in 2022 to 1.25 MMbbls/day in 2040. According to our carbon emissions modelling, this production decline is accompanied by a near tripling of carbon intensity over next twenty years to 0.21 t CO_2 eq/bbl in 2040 resulting in upstream associated carbon emissions of 94 MM tCO_2eq in 2040. If carbon taxes are implemented at the level and timing suggested by the net zero by 2050 target, the upstream will be exposed to a ~ $4 billion payout in carbon tax receipts by 2040. These results are the outcome of intersecting Nigeria's forecast depletion rate with critical elements of the climate change policy architecture.

Summarily our results corroborate the earlier work of Iledare & Pulsipher (2000) in the industry performance but is unable to show that Nigeria's supply declines with increased oil prices. The calculated indices suggest that Nigeria's production profile is already consistent with climate change objectives – declining production, declining reserves addition, EDI converging to 1. However, just transition imperatives will need to be brought to bear on the fiscal import of these supply side pressures on an oil dependent and OPEC member country. Modelling results also suggest that Nigeria's production has always been coordinated with that of OPEC. Furthermore, applying key policy elements of climate change policy reveal the implied emissions to be expected and resulting associated costs. The additional work required to deepen our understanding of oil depletion within climate change context involves improving operational data collection to piece together upstream emissions picture. This is important work necessary to specify the carbon intensity of production in the Niger-Delta, pursue plans to minimize upstream oil emissions, evaluate the impact to project economics from imposing the carbon tax as well as strengthen the governance around potential carbon tax receipts.

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