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The Dynamics of Low-carbon Energy Transitions and Net-zero Emissions Toward Energy Security and Climate Goals in Nigeria

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Dedication

I dedicate this thesis to the memory of my lovely Sister, Iyadunni Imeriohe SHARI, who passed on to glory on 20 May 2016. She was an inspiration for my academic prowess, and I am pained that you couldn't see me graduate. Rest on!

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Abstract

The energy situation in most developing countries is similar because it is characterized by a large deficit of modern energy supply, heavily dependent on fossil sources, and thus struggles to attain sustainable development and climate goals. All efforts toward achieving climate goals should strategically support energy security, which considers meeting unmet energy demands and doing so with affordable clean energy resources. Using the Nigerian energy sector as a model system, this dissertation explores and investigates the dynamics of low-carbon energy transitions and net-zero emissions for energy security and climate goals. To do this, participatory and explorative scenarios and system dynamics modelling approaches were employed. These methods explore (i) stakeholders' perspectives on low-carbon development, (ii) energy system modelling based on some open-source energy model paradigms, and (iii) dynamics of clean cooking and cook fuel, which represent a rationale for energy transition pathways. The outcomes from the research showed a systematic clean energy development and planning framework. From stakeholders' viewpoints, the results also revealed that to achieve a realistic low-carbon energy development, appropriate financing tools, clean technology (especially solar energy), energy-efficient appliances, and significant policy leverage points are needed. In addition, advocacy in energy efficiency behavior builds confidence in energy efficiency standards. Further analysis showed that energy efficiency would play a significant role in the energy transition agenda, both in ensuring the security of energy and achieving climate goals by saving up to about 19,000 PJ of energy, 3.1 trillion USD, and abate about 11.42% of CO₂ emissions by 2050. Natural gas serves as a transition fuel and a significant resource for the short and medium-term for clean cooking, while solar energy technologies will become the most accepted and relevant source in the energy mix. Green hydrogen fuel cells, and distributed generation would extensively support the Nigerian green initiative to achieving net-zero emissions through deliberate investment in solar technology. Planning a clean energy future from a stakeholders' perspective provides appropriate modeling assumptions for energy systems' modeling to generate relevant policy insights for energy planners, investors, and researchers. This policy instrument should support deliberate advocacy for solar energy technologies and energy efficiency standards and behavior. Finally, this study provides some recommendations for policymakers to consider an inclusive approach in planning for a clean energy future.

Keywords: Net-zero emissions, Nigerian energy sector, OEMOF, System dynamics, Stakeholders' perspective, clean cooking.

Résumé

La situation énergétique dans la plupart des pays en développement est particulière car caractérisée par un important déficit d'approvisionnement en énergie moderne, fortement dépendant des sources fossiles, et peine ainsi à atteindre les objectifs de développement durable et de climat. Les efforts visant à atteindre les objectifs climatiques devraient soutenir stratégiquement la sécurité énergétique, qui envisage à la fois de répondre aux demandes énergétiques non satisfaites et de le faire avec des ressources énergétiques propres et abordables. En utilisant le secteur de l'énergie nigérian comme système modèle, cette thèse explore et étudie la dynamique des transitions énergétiques à faible émission de carbone et des émissions nettes nulles pour la sécurité énergétique et les objectifs climatiques. Pour ce faire, des scénarios participatifs et exploratoires et des approches de modélisation de la dynamique des systèmes ont été utilisés. Ces méthodes explorent respectivement 1) les perspectives des parties prenantes sur le développement à faible émission de carbone ; 2) modélisation du système énergétique basée sur certains paradigmes de modèles énergétiques open source ; et 3) la dynamique de la cuisson propre et du combustible de cuisson, qui constituent une justification des trajectoires de transition énergétique. Les résultats de la recherche ont montré un cadre systématique de développement et de planification de l'énergie propre. Les résultats ont également révélé, du point de vue des parties prenantes, que pour parvenir à un développement énergétique réaliste à faible émission de carbone, des outils de financement appropriés, des technologies propres (en particulier l'énergie solaire) et des appareils économes en énergie, des leviers politiques importants sont nécessaires. En outre, la promotion d'un comportement en matière d'efficacité énergétique renforce la confiance dans les normes d'efficacité énergétique. Une analyse plus approfondie a montré que l'efficacité énergétique jouerait un rôle important dans le programme de transition énergétique, à la fois pour assurer la sécurité de l'énergie et atteindre les objectifs climatiques en économisant jusqu'à environ 19 000 PJ d'énergie, 3,1 billions de dollars, et en réduisant environ 11,42 % des émissions de CO₂ d'ici 2050. Le gaz naturel sert de carburant de transition et de ressource importante à court et moyen terme pour la cuisson propre, tandis que les technologies d'énergie solaire deviendront la source la plus acceptée et la plus pertinente dans le bouquet énergétique. Les piles à combustible à hydrogène vert et la production distribuée soutiendraient largement l'initiative verte nigériane visant à atteindre des émissions nettes nulles grâce à des investissements délibérés dans la technologie solaire. La planification d'un avenir énergétique propre du point de vue des parties prenantes fournit des

hypothèses de modélisation appropriées pour la modélisation des systèmes énergétiques afin de générer des informations politiques pertinentes pour les planificateurs énergétiques, les investisseurs et les chercheurs. Cet instrument politique devrait soutenir un plaidoyer délibéré en faveur des technologies de l'énergie solaire et des normes et comportements en matière d'efficacité énergétique. Enfin, cette étude fournit quelques recommandations aux décideurs politiques pour qu'ils envisagent une approche inclusive dans la planification d'un avenir énergétique propre.

Mots-clés : Émissions nettes nulles, Secteur énergétique Nigérian, OEMOF, Dynamique du système, Perspective des parties prenantes, Cuisson propre.

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List of Abbreviations (Acronyms)

\$Bn	US Billion Dollars
3Es	Energy Economic-Environment
AC	Alternative Current
Acs	Air Conditioners
API	Application Programming Model
AU	African Union
BAU	Business As Usual
BMBF	Bundesministerium für Bildung und Forschung (Federal Ministry of Education and Research)
BOS	Balance of the System
CCG	Climate Compatible Growth
CCS	Carbon Capture and Storage
CLD	Causal Loop Diagram
CO ₂	Carbon dioxide
CSDK	Country-based Starter Data Kit
DC	Direct Current
DD	Dry-season Day
DisCos	Distribution Company
DN	Dry-season Night
ECN	Energy Commission of Nigeria
ECOWAS	Economic Community of West African State
EGD	European Green Deal
EMP	Energy Modeling Platform
ETP	Energy Transition Plan
FCT	Federal Capital Territory
FiT	Feed-in Tariffs
FOREX	Foreign Exchange

GDP	Gross Domestic Product
GenCOs	Generation Companies
GHG	Greenhouse gas
GIW	Global Warming
GtCO ₂	Gigatonne Carbon dioxide
GUI	Graphical User Interface
GWh	GigaWatt hour
H ₀	Null hypothesis
H ₂	Hydrogen
H _a	Alternative hypothesis
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
kWh	KiloWatt hour
LD	Linear Programming
LOHC	Liquid Organic Hydrogen Carriers
LPG	Liquefied Petroleum Gas
MILP	Mixed-Integer Linear optimization model
MJ/Kg	MegaJoule per Kilogram
MJ/M ³	MegaJoule per cube meter
MW	MegaWatt
NBS	National Bureau of Statistics
NDCs	National Determined Contributions
NELG	Nigeria Energy Label Guide
NEMP	National Energy Master Plan
NEPA	National Electricity Power Authority
NERC	Nigerian Electricity Regulatory Commission

NG	Natural Gas
NGOs	Non-Governmental Organization
NLPG	Nigerian Liquefied Petroleum Gas
NPS	Nigeria power sector
OEMOF	Open Energy Modelling Framework
OSeMOSYS	Open Source Energy Modeling System
PA	Paris Agreement
PJ	Petajoules
PPP	Public-Private Partnerships
PYOMO	Python Optimization Model
R&D	Research and Development
RD	Rain-season Day
RE	Renewable Energy
RES	Reference Energy System
RET	Renewable Energy technology
RLI	Reiner Lemoine Institut
RN	Rain-season Night
SD	System Dynamics
SDGs	Sustainable Development Goals
SFD	Stock and Flow Diagram
SON	Standard Organization of Nigeria
SPSS	Statistical Package for the Social Sciences
SSA	Sub-Saharan Africa
SSPs	Shared Socio-Economic pathways
TCN	GigaWatt
TEMBA	Energy Model Basic for Africa
TIES	Tertiary Institutions Entrepreneurship

U4RIA	Ubuntu Retrievable Reusable Repeatability Reconstructability Auditability
UNDESA	United Nations Development of Economic and Social Affairs
UNDP	United Nations Development Program
WASCAL	West African Science Service Centre on Climate Change and Adapted Land Use
WB	World Bank
WFH	Work from home

CHAPTER ONE

INTRODUCTION

1.0. Introductory Content

It has been proved that climate change has an unprecedented impact on both developed and emerging nations including their agriculture and food supply, air quality, energy system, health sector, ocean and marine resources, freshwater resources, and forests and the ecosystem (Hayhoe *et al.*, 2018; Atwoli *et al.*, 2022). Although the impact varies from one nation to another, the most affected are the emerging economies, which contribute the least to greenhouse gas emissions. It is also worth noting that the impact is widespread and international cooperation is thus required. This implies that all nations must actively respond to climate change impacts by cutting down local emissions of greenhouse gases. In response to abating emissions, about 192 countries have agreed to the Paris Agreement¹– a legally binding international treaty on climate change (UNFCCC, 2015). The Paris Agreement aims to hold the increase in the global average temperature to well below 2°C above pre-industrial levels, and thereafter pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels (UNFCCC, 2015).

The energy sector is the main emitter of greenhouse gases, which is responsible for climate change and global warming, it also accounts for more than two-thirds of global greenhouse gas emissions (Walton, 2020). This implies that modernizing the energy sector is crucial for cutting global emissions (Biol, 2020). Recently, several countries like Germany (BBC, 2020) have made efforts and plans to retire their fossil fuel plants in response to achieving their low-carbon energy strategies in their carbon-neutral and net-zero emissions framework. In recent times, many developed and very few developing countries like Kenya and South Africa (IEA, 2020a) have made efforts to gradually transition their transportation sector from fossil fuel-based to green electricity, hydrogen, and fuel-cell powered systems. In light of the serious energy deficits in the world, particularly in sub-Saharan Africa (SSA), it was debated whether financing a low-carbon transportation system would be appropriate (Collett *et al.*, 2021; Dioha *et al.*, 2022).

¹The Paris Agreement is a legally binding international treaty on climate change. It was adopted by 196 Parties at the UN Climate Change Conference (COP21) in Paris, France, on 12 December 2015. It entered into force on 4 November 2016.

Globally, in 2010, there were about 1.3 billion people without access to modern electricity, most of them in SSA (González-Eguino, 2015). According to a World Bank report, in 2019, the number of people without access was reduced to 759 million, this implies that about 42% of people in 2010 were electrified (World Bank, 2021). This improved energy access is due to the decentralised renewable-based solutions where more people are connected to electricity via mini-grids and solar home systems (World Bank, 2021). Despite the rapid energy access through the deployment of solar mini-grids, most developing countries, including the least-developed countries, have yet to achieve reliable and sustainable energy security and thus experience low energy production and per capita consumption (Traeger *et al.*, 2017). Already, SSA countries have a large share of energy poverty (González-Eguino, 2015), making them the most vulnerable in the world (Morris *et al.*, 2017) to change (Baarsch *et al.*, 2020; Atwoli *et al.*, 2022).

Further, access to clean cooking fuel is an important part of the modern energy sector, but it is not without its drawbacks. In 2019, about 2.6 billion people remained without access to clean cooking (around one-third of the global population) (World Bank, 2021). The clean cooking initiative has not experienced the required scaling, especially in SSA, where only 17% of the population currently uses clean solutions (Khavari *et al.*, 2023). The rate of clean cooking adoption in the region has experienced several limitations, including cultural, social, economic and infrastructure constraints, although significant growth was noticed in modern electrification in some countries of the region (Vigolo *et al.*, 2018). In the SSA region, the adoption of clean cooking is daunting, as about 910 million people in the region lack access to clean cooking. Although renewable energy sources are most dynamic in the electricity sector, reaching a share of around 25 per cent in 2018, progress in their application in heat (*i.e.*, cooking), and transport sectors has been much slower (World Bank, 2021).

Further, energy intensity (in the form of energy efficiency) is an energy standard that could enhance energy efficiency and thus could support the clean energy transition agenda. The International Energy Agency (IEA) report referred to energy efficiency as the first fuel in the clean energy transition agenda as it provides some of the quickest and most cost-effective carbon dioxide (CO₂) mitigation options while lowering energy bills and strengthening energy security (IEA, 2022a). Energy efficiency is indeed a vital energy management strategy in developing a country's clean energy transition framework. This is especially true in developing countries that require cheap and affordable modern energy.

Energy demand across the residential, transport, industrial and service sectors has risen worldwide; this increase in energy demand is largely due to the following: (i) an increase in the Gross Domestic Product (GDP) of countries, (ii) an increase in population, (iii) industrialization, and (iv) improved income and welfare, among other factors. Conversely, a recent report by the IEA (IEA, 2020) reported that energy demand is expected to reduce by 5%, which could be due to the unprecedented outbreak of the COVID-19 pandemic (Cozzi *et al.*, 2020). Amongst this, the global electricity demand is set to decrease by 2%, oil demand to reduce by 2%, demand in natural gas brought down by 3%, coal by 7%, and energy investment reduced by 8%. Despite several anomalies in the energy paradigm, renewable energy will experience an increase of about 2% (Cozzi *et al.*, 2020). The question is, what have the unprecedented changes in energy demand translated to in the development of low-carbon energy transitions in emerging economies? Energy efficiency can serve as a significant measure to manage the unprecedented growth in energy demand. Most emerging economies, especially in SSA, still struggle to meet their basic energy needs, exacerbated by the recent surge due to the COVID-19 pandemic.

On the contrary, according to recent international perspectives, the unprecedented implication of the COVID-19 pandemic could lead the way to better penetration of Renewable Energy Technology (RET) among developing countries. Nonetheless, if proper planning is not sustained, the aftermath of RET use could lead to a more devastating outbreak in the continued use of fossil energy sources, thereby reversing the current trend in RET deployment and hampering the clean energy transition process.

The evolution of clean energy in SSA is highly controversial and fraught with uncertainties; this is largely due to a double-hydra challenge facing the region's energy sector, which can be categorised as having a low access rate with very little emissions, yet still needing to mitigate under the best international agreements (Roser, 2020). It, therefore, suggests that the transition strategies for the region should deliberately entail improving energy access while avoiding the pitfalls of the developed countries (Berry-Weiss, 2022). In that, electrification strategies should contribute to improving the people's electricity consumption per capita and strategically harnessing the vast available clean energy resources in the region (Olanrele & Fuinhas, 2022). Unfortunately, the Nigerian power sector has experienced years of modern electricity shortage and several daily load shedding, and as such, has yet to meet its daily energy demand (Babatunde *et al.*, 2023). This implies that comprehensive planning of the energy transition is of utmost importance, and the Nigerian energy transition agenda should be put in the right

Moallemi & Malekpour (2017) referred to energy transition processes as complex processes that require different actors and present a deeply uncertain future in their processes. Therefore, approaches that would model energy planning transitions should consider future uncertainties and employ a participatory modelling approach. Hence, planning a low-carbon energy development strategy should consider key stakeholders in planning the transition processes. Who are these stakeholders? Franklin (2020) described stakeholders as people who are influenced by or can influence the activities of others. Their participation in the clean energy development process is crucial since they can influence the planning processes and disrupt or contribute to its success. Through the review of national documents and relevant literature, interactions and surveys, we can find out stakeholders' preferences and delineate issues creating uncertainties in planning processes, and understanding value-producing solutions (Carnahan *et al.*, 2010). The values that can be produced from stakeholder interactions include representativeness, transparency, accessibility, responsiveness, accountability, and sustainability (Franklin, 2020). A holistic energy planning framework would therefore mean that decision-making for the development of a clean energy future should utilize outcomes from a successful stakeholders' engagement. Since evaluating and modelling energy transition would require a systemic transformation of our energy systems, there is a need to consider relevant stakeholders' opinions to achieve a sustainable outcome (Freudenreich *et al.*, 2020).

The role of scientists, engineers, energy users, and technicians is crucial in achieving a sustainable and clean energy future by scientifically supporting the planning processes and conjugating the social aspects with economic and environmental sustainability (Hettinga *et al.*, 2018). In this regard, participatory, mathematical, and computer-based modelling tools will be useful to scientifically translate policy into modelling assumptions through scenarios (Krumm *et al.*, 2022; Kurniawan *et al.*, 2022). Scenarios are commonly used to facilitate short and long-term policy decisions associated with climate change, given the uncertainty in the underlying environmental, social, political, economic and technological factors (Nebojsa *et al.*, 2000).

According to the Intergovernmental Panel on Climate Change (IPCC), a scenario is a coherent, internally consistent and plausible description of a possible future state of the world (IPCC, n.d.). A scenario is not a forecast, rather, each scenario is one alternative image of how the future can unfold (Faisal *et al.*, 2021; France *et al.*, 2013).

systems for the future, and also enhance evaluating government-pledged goals without leaving anyone behind (Benedict, 2017). It is commonly expressed that there is a disconnect between policymakers and scientific outcomes; there is, therefore, a need to bridge this unprecedented gap by using scenarios. As such, scenarios could enable a keen insight into the future to explore the energy transition framework. Consequently, the outcomes will yield realistic insights for policymakers and energy planners and thus develop and strengthen the economic prowess of such nations, especially in sub-Saharan African countries.

In light of these, several efforts to reform the energy sector have been made, through energy policy and planning reforms, and even liberalization of the power sector towards enabling the people of SSA to have access to both clean cooking and clean, affordable and reliable energy access. All these efforts have yielded little result, as most people in the region still have limited access to modern energy. The effect of the energy demand-supply imbalance has therefore left the citizens of the region, especially in Nigeria, with no choice but to resort to expensive self-generated electricity from diesel/petrol generators, thereby polluting the immediate environment and causing other environmental and health hazards (Ediagbonya *et al.*, 2022; Nubi *et al.*, 2022; Journal & Pure, 2023). The large unmet electricity demand has further caused the prices of goods and services to spike, reducing the purchasing capacity of households and increasing the poverty rate among the populace (Oyedokun *et al.*, 2022). The impact of energy insufficiencies, including access to clean cooking, has been exacerbated in rural areas due to weak infrastructure and unreliable manpower (Ogunro, 2022).

On this premise, this study would systematically design a dynamic approach to explore the dynamics creating uncertainties in planning a low-carbon energy paradigm, including an aim to abate emissions to zero from the electricity and heating sector (clean cooking), while investigating approaches to sustainable energy access. Therefore, the overall research aims of this study is to address several thematic issues affecting the region based on the following research framework: (i) to explore the dynamics of stakeholders on energy transitions and net-zero transition plan, (ii) to explore a least-cost optimization modelling framework, (iii) to explore the role of clean cooking and green hydrogen, with regards to the energy transition, and (iv) to consider the perspectives of climate change and energy system modelling.

This introductory section describes the rationale behind this study, the scope of the research, and explains the fundamental background and purpose of the current study. The introduction is sectioned into five major headings including (i) the background which gives a summary of the

thesis, (ii) the problem statement which gives the declaration of the study problem, (iii) the aim and objectives of the study, (iv) research questions, and (v) significance of the study that explains the research goals and hypothesis.

1.1. Background

Several countries have signed the treaty to agree to cut their emissions to combat the impacts of climate change, through adaptation and/or mitigation strategies (UNFCCC, 2015). There is a spreading argument that developed economies are largely responsible for nearly 80 per cent of all human-related CO₂ emissions between 1850 and 2011 (GHOSH, 2022), which has led to the catastrophic impacts of climate change, as a result of emissions from several years of fossil fuels burning. However, emerging economies, especially African countries, with little coping capacity and very weak adaptation protocols, are at the receiving end of the negative impact of the continued emissions from developed countries. Nevertheless, the developing nations of African countries, especially in the SSA region need to build resiliency against climate impacts, especially in the energy sector (Morris *et al.*, 2017; Baarsch *et al.*, 2020; Atwoli *et al.*, 2022) and also manage the twin-like challenge of energy access and achieving carbon neutrality (World Bank, 2021). Achieving these will mean that countries in the region would consider establishing a robust clean energy framework that would translate climate goals into sustainable policies and determined implementation, capable of supporting its short-, mid-, and long-term clean energy transition strategies.

Planning a clean energy transition paradigm has led to the development of several climate policy debates among policymakers worldwide (Roggema, 2020), and that has motivated major climate change decisions and climate policy ambiguities (Fleming & Howden, 2016). As nations transition to a low-carbon energy future, it could pose some risks and uncertainties in deploying renewable energy technologies (IRENA, 2019; Taebi *et al.*, 2020). Connor *et al.* (2018) identified and explored seven categories of risks and uncertainties in the UK's clean energy uptake. Connor recognized markets, users, data and information, supply mix, policy, investment conditions, and networks, as the main sources of risks and uncertainty in the transition to a clean energy paradigm, and by extension could be considered for other emerging economies in Africa. On the other hand, given the advances in technology, culture could play a significant role in energy transition, as it could guide energy planners for innovative and sustainable energy transitions (Sovacool & Griffiths, 2020). On this view, developing countries despite their numerous energy challenges could leverage recent innovations to improve their

nation's energy outlook.

Nigeria, known for its economic strength, vast human capital, and vast natural energy resources, with its significant influence in the SSA and among the West African countries, still struggles to meet its national energy demand (Owunna & Obeagu, 2022). With a significantly large youthful population and a high dichotomy between the rural and urban areas and dwellers, the country needs to be deliberate about meeting its vast energy needs (Shari *et al.*, 2022). This would enable the country to strengthen its fragile economy and meet the energy demand of its growing population. For this reason, there would be a need to build a strong institution of an energy portfolio that would holistically consider key actors' perspectives in the energy sector whose views and opinions on planning a clean energy sector will be all-inclusive and capable of managing effectively many uncertainties in the planning processes even as the country planned its energy transition across all sectors including clean cooking (Shari *et al.*, 2023), transportation and power.

Interest in energy transition has escalated over the years, as governments and organizations look ahead to the shift in the country's energy portfolios, which has led to its recent legislation, i.e., the Climate Act in 2021 (*Climate Change Act*, 2021). However, a complete transition to clean energy will require the involvement of multiple stakeholders because of vested interests in the energy sector. There are considerable differences in the pace and underlying motivations of the energy transition in the different geographical contexts across the developing countries; however, the pace of Nigeria's clean transition process is slow, and this could be attributed to the large fossil fuel resources (Adewuyi *et al.*, 2020). Hence, there is a need for a better understanding of the energy transition strategies in different contexts, timescales, and outlooks that would enhance the cooperation among involved actors, as against working in silos to achieve personal interest and gain interest in the energy sector.

The work of Kleanthis *et al.* (2022), examines stakeholder perspectives on energy transition and reveals that achieving a timely transition in the energy sector depends on the national context. It implies that achieving a just energy transition is largely dependent on country-specific factors such as infrastructure, economy i.e., GDP, environmental and climatic conditions, etc. In a similar view, Sentinel, (2023) suggested that stakeholder perspectives on the energy transition strongly depend on contextual factors underlying the need for policies tailored to the transition issues and challenges in the different regions. This implies that the concept of the energy transition is complex as no one approach fits all regions because every region is peculiar in its

pathway to its future energy paradigm, and more so, they have not developed at the same pace (Bridge & Gailing, 2020). Therefore, stakeholder perspective on energy transition should be prioritized for a proper understanding of the dynamics and putting into perspective the complex issues underlining a region's future clean energy that could either make or mar its clean energy planning portfolio. Thus, there is a need for a systematic framework that conceptualizes the concerns and opinions of stakeholders about a region's energy transition plans.

Nigeria, being a significant energy giant in the SSA region, needs not to only lead the way in the exploring and refining of fossil fuel resources, but also commit its national energy policies to achieving clean energy transition strategies. Consideration of a stakeholder framework as an inclusive approach to exploring and investigating the country's future clean energy interest is a clarion call to developing Nigeria's future energy outlook (Edomah *et al.*, 2021a).

The stakeholders' role in the energy transition is a phase that investigates national needs, and interests that serve all, in an all-inclusive manner. However, there is a need to translate the stakeholder's interest in energy modelling assumptions that inform energy transition policies that would also enable the country's Net-zero emissions agenda. Although Net-zero emissions are more than a scientific concept or a technically determined target, it is a frame of reference through which global action against climate change can be (and is increasing) structured and understood (Fankhauser *et al.*, 2022). This implies that achieving successful Net-zero emissions across all sectors is more of a national concern and has a high tendency to attract climate co-benefits ² while advancing global emission concerns of temperature reduction to 1.5°C above pre-industrial levels (IPCC, 2018b).

The clean energy era seems like a *long journey to freedom* for most developing countries of SSA because the process of clean transition requires some level of technicalities and changes in human behaviour or lifestyle that is cost-driven. As such, planning to both improve energy access and curtail emissions across the energy sector could be very daunting, especially in evaluating its sustainability in the long term. The energy sector of developing countries including Nigeria is known for large unmet demand, and having more people without clean cooking, weak and old infrastructure, low-income rates, high levels of illiterate and large energy deficit in the rural areas. These and more present significant risks and uncertainties to planning future clean energy agenda in the developing countries. However, energy models could serve as cheap alternatives to planning and provide insightful pieces of evidence for developing clean energy frameworks and strategies. Also, models could enhance translating energy modelling assumptions into values and astute assumptions about the future energy evolution, and thus

inform energy transition policies.

Previously, most developing countries have employed the use of commercially sourced models to develop their low-carbon energy framework. However, the commercial models are operated like a black box, where the modeller has little or no knowledge of the internal constraints and function of the model, thus posing a challenge for inexperienced local users (Pfenninger *et al.*, 2018). Also, most commercially available models were developed and designed for the energy sectors of the developed countries. These models were developed especially to plan their energy systems after the 1970s world oil crisis ⁴, and as such might not be compatible with the developing countries' social, technical, economic, and environmental situation (Millot *et al.*, 2020; Pfenninger *et al.*, 2014). Another restriction factor is that commercial models could be very expensive, and most developing countries struggle to meet financial commitments (Pfenninger *et al.*, 2014). Recently, advancements in open-source energy models have brought about transparency and open availability of energy models and data to overcome several bottlenecks in commercially available models (Pfenninger *et al.*, 2018). As such, they have found applications in some developing countries to provide insightful scenarios for their clean energy planning strategies (Howells *et al.*, 2011; Kazmi *et al.*, 2021).

² Co-benefits are World Bank financing that supports climate action while also furthering development objectives ³ Something that looks very difficult to achieve, considering the current realities. getting freedom (from energy poverty) after a very long struggle due to the courage of all the people including policymakers who sacrificed so much for equality and energy security in the country. This is applied to the energy sector as achieving energy access with curtailing emissions including power, heating and cooking, transportation

In summary, many years of fossil fuel exploitation have been catastrophic to the world, including the developing countries that are found to be the most vulnerable (Wilkinson *et al.*, 2007). Several nations and cities have felt the impact of climate change as a result of global warming caused by emissions from burning fossil fuels. Many countries have made commitments to explore green technology to either achieve their low carbon energy development, net-zero emissions targets, and/or to achieve the Nationally Determined Contributions ⁵(NDCs); the goals are the same – to abate global emissions (Teresa *et al.*, 2023). It is also worth noting that green hydrogen through stakeholder opinion, intends to ameliorate bottlenecks in planning and uncertain circumstances, and could enhance and reduce risk in planning energy transitions and explore open-source models to gain relevant insights and modelling assumptions that inform energy transition policies.

Therefore, this study explores the clean energy planning case of developing countries from a stakeholder perspective, and insights from the analysis of stakeholders' opinions will be employed to gain insight into the clean energy paradigm through modelling. Policy insights were obtained by employing open-source modelling tools to develop scenarios for different planning paradigms while exploring diverse energy mixes including green hydrogen technologies as a future green fuel, and nuclear energy.

⁴Oil crisis a sudden rise in the price of oil that is often accompanied by decreased supply.

⁵Nationally determined contributions (NDCs) are at the heart of the Paris Agreement and the achievement of its long-term goals. NDCs embody efforts by each country to reduce national emissions and adapt to the impacts of climate change.

1.2. Statement of the Problem

This sub-section will rigorously examine the study research problems according to the following perspectives i) synergy among energy stakeholders; (ii) modelling national energy transition paradigm; (iii) distributed energy system; (iv) evidence of natural gas as transition clean cooking fuel.

i. Synergy among energy stakeholders

Several international and national agencies including professionals from the academia have critically explored the issues of energy poverty and insecurity in developing countries and Nigeria (González-Eguino, 2015; Ashagidigbi *et al.*, 2020; Nduka, 2021; Apergis *et al.*, 2022), and including issues of scaling up renewable energy deployment as a clear and timely opportunity for the African economies to benefit from the global green transition (Medinilla & Sergejeff, 2023). Unfortunately, few have translated to improving electrification let alone a positive impact on the livelihood of its citizens (Djala, 2022). Yet, Ogunleye revealed that there is a disconnect between government agencies and the concerned stakeholders in the dispatch of energy policies and their implementation (Ogunleye *et al.*, 2022). The study further suggested that there is a need for different actors in the energy value chain to consolidate efforts and policies that will enhance energy challenges in the country, especially on the issue of energy transition. Efficient stakeholder collaboration would enable a sustainable clean energy transition and support effective planning in the sector.

ii. Modelling the national energy transition paradigm

An effective stakeholder collaboration could support the transition paradigm, which is not evident in Nigeria's energy sector using open-source models. Energy models are an enabler that serves as a connecting bridge between several government agencies, scientists, technicians, engineers, and other stakeholders in the energy sector. Energy models employed for national planning are usually commercially sourced and not open to users. Such models, therefore, have limited transparency on the modelling outcomes and prevent countries from owning their transition paradigm. To ameliorate this bottleneck in energy system modelling, the adoption of the U4RIA¹ principles and guidelines on energy modelling processes, tools, and data collection could significantly enhance modelling planning efforts in developing countries (Howells *et al.*, 2017).

¹U4RIA stands for Ubuntu, Retrievalability, Reusability, Repeatability, Reconstructability, Interoperability and Auditability.

This principle recommends that the modelling process should be (i) engage communities, (ii) have easy access to data, (iii) reusable, (iv) repeatable, (v) interoperable - enable modelling exchange, and (vi) be accountable. However, the subsequent section would shed more light on the principles mentioned earlier.

iii. Distributed energy system

Examining the Nigerian power challenges from the supply side, electricity generation is largely dependent on a dual-based energy mix of gas and hydropower. About 78% of its generation comes from gas-fired power plants, while 21% is from hydropower generation.² This unsustainable energy mix is buttressed in a 2020 energy situation where about an average of 24,683 GWh and 7,686 GWh were generated from gas and hydropower, respectively and an insignificant amount of about 42.0 GWh was obtained from solar (IEA, 2022c). While Electricity from other sources such as bioenergy, solar, wind and other fossil sources is marginal, the use of captive diesel generators for electricity generation is alarming. This implies that energy security in Nigeria's power sector is weak and it could be due to the heavily dependent centralized energy system which has faced several challenges, from electricity theft due to a weak monitoring network, consistent grid collapses often due to obsolete infrastructure and corruption, large power loss due to power transmission through a long distance, among others (Toktarova et al., 2019; NERC, n.d.). A decentralized network (where the energy system is managed and regulated by the states and/or region) through a distributed power system could help ameliorate these challenges and it is investigated in this current study.

iv. Evidence of natural gas as a transition to clean cooking fuel.

The scaling up of low-carbon energy technologies has been narrowed in terms of implementation as it has focused more on the power sector, with little attention on the heat and cooking sectors. In Nigeria, a lack of adequate information with little evidence-based research has thwarted the planning strategies for clean cooking adoption and how Liquefied Petroleum Gas (LPG) could serve as a transition fuel for meeting heating and cooking demand in the Nigerian energy sector. A neglect of the heating and cooking sector will slow down the realization of the climate goals. While the energy supply-demand gap is enormous, clean cooking using electricity as fuel might be

² <https://www.statista.com/statistics/1237541/nigeria-distribution-of-electricity-production-by-source/#:~:text=Natural%20gas%20is%20by%20far,percent%20of%20Nigeria's%20power%20production.>

rigorous and complex while frustrating the climate goals. There is a need to explore the clean cooking sector with alternate clean cook fuel.

The overall challenges faced in the Nigerian power sector can largely be attributed to little or no synergy between energy stakeholders in the power sector to achieve uniformity of energy policy and its implementation, twinned with developing a concise strategic and transparent low-carbon energy strategy that is open and guided by the U4RIA modelling guidelines.

1.3. Research Questions

The research questions of the study are:

- i. what are the main views and perspectives of stakeholders that would enhance energy security and support energy transition towards the country's climate goals in the short-, mid-, and long-term policy?
- ii. are open-source modelling tools capable of capturing developing countries' asymmetric energy sector and its dichotomy, and which modelling tool?
- iii. how would the policy outcomes from (i) translate into modelling assumptions that explore Nigeria's emission reduction strategies and
- iv. what technology and economic options can be explored to achieve universal access and zero emissions targets?

1.4. Aim and Objectives

To achieve the aforementioned research questions, the aim and objectives are as follows:

Aim: The study aims to explore the dynamics of low-carbon energy transitions and net-zero emissions energy planning based on stakeholders' perspectives towards energy security in Nigeria's energy sector and lessons for developing countries.

Specific objectives: the set aim is expected to be achieved according to the following specific objectives to:

- i. develop an integrated dynamic model that explores stakeholder perspectives on planning energy transition strategies for low-carbon development in the Nigerian energy sector and as input for energy models;

- ii. investigate the compatibility of open-sourced modeling tools capable of translating modelling assumptions into energy policy that supports low-carbon energy implementations in a typical developing country archetype, and;
- iii. develop possible development scenarios and pathways using open-source modelling tools based on analysis from stakeholders' perspectives framework;
- iv. examine a distributed power sector and clean cooking that explores appropriate policy implications for an energy transition plan and a net-zero emission power sector.

1.5. Research Hypothesis

The research hypothesis presents a tentative statement expressing what the author envisages as the research outcomes based on existing and profound knowledge. To do this, the study hypothesis is divided into two thematic sections.

1.5.1. Hypothesis based on stakeholders' perspective

This study aims to answer the following research questions:

- i. Which clean energy technologies should be prioritized to plan a low-carbon future?
- ii. What would this transition look like in achieving a sustainable future?
- iii. What financial innovation would most be relevant in the power sector to enhance a low-carbon future?
- iv. How would the aforementioned variables affect the Nigerian energy transition?

This research considers one dependent variable (i.e., energy transition), and four independent variables (i.e., technology, motivation, finance, information) to develop the study's hypothesis. The four hypotheses considered are presented below. Ho and Ha represent the null hypothesis and alternative hypothesis, respectively.

Ho: innovation does not have a significant effect on energy transition

Ha: innovation has a significant effect on energy transition

Ho: technology does not have a significant effect on energy transition

Ha: technology has a significant effect on energy transition

Ho: motivation does not have a significant effect on energy transition

Ha: motivation has a significant effect on energy transition

Ho: finance does not have a significant effect on energy transition

Ha: finance has a significant effect on energy transition

1.5.2. Hypothesis based on energy transition modelling

Low-carbon energy development is relatively slow in developing economies due to many factors that were previously discussed. Its heavy dependence on fossil fuel energy could hinder the transition process. Models could be significant in providing insight; however, they could also be expensive and often operated as a Blackbox. Hence, model transparency is key to a sustainable future of clean energy. As a result, open-source models are compatible with the dichotomy of regional energy systems when compared to their expected output. This section provides an inclusive background.

Furthermore, the hypothesis based on the energy transition model is as follows:

- i. Could information obtained from a stakeholder assessment be translated into energy modelling assumptions to plan clean energy strategies for developing countries?
- ii. If the Nigerian power sector considers pragmatic actions to achieve net-zero emissions in the power sector and enforces synergy between energy stakeholders, including agencies, they will simultaneously achieve energy security and climate goals.
- iii. Open-source modelling tools can capture asymmetrical attributes in developing countries' energy planning frameworks for low-carbon development.
- iv. If Nigeria considers a distributed power system in its energy planning approach, then the electricity demand gap will be met.

Exploring hydrogen technology as a future clean fuel in the Nigerian energy mix could enhance its net-zero emissions target in the long term.

In the alternate hypothesis, green hydrogen technology as a future clean fuel will not have a significant effect on the country's net-zero transition plan in the long term.

1.5.3. Hypothesis based on clean cooking transition

When would the utilization of clean cooking fuel, especially natural gas (a transition fuel in Nigeria), be fully adopted in the heating and clean cooking sectors across urban and rural households in Nigeria?

Sule *et al.* (2022) revealed that infant mortality is directly linked to energy poverty in most African countries. Access to household clean energy (in the form of clean cooking) has a significant tendency to avert indoor air pollution in developing countries that causes millions of infants and premature deaths among the most vulnerable segment of the population (Imelda, 2020). About 17% have access to clean cooking in SSA, while about 94% of Nigerians do not have access to clean cooking in 2022 according to the National Bureau of Statistics (NBS) (Odunewu, 2022). However, some factors could impede or facilitate the adoption of clean cooking in developing countries.

This sub-section, therefore, hypothesizes that:

- i. If household income increases, the transition to clean cooking would be faster and timelier,
- ii. Larger household sizes will facilitate the spread of clean cooking among consumers,
- iii. Urban households' consumers are likely to adopt clean cooking and transition faster to clean cooking than rural households,
- iv. The more households communicate and get in touch, the adoption of clean cooking will become more prevalent in urban and rural households,
- v. An increase in clean cooking fuel (natural gas) will discourage households from adopting clean cooking interventions.

It is pertinent to clarify that the assessment of clean cooking adoption for the clean transition does not involve statistical hypothesis testing. This implies that a null hypothesis will not be required.

1.6. The Significance of the Study

This subsection explains the overall impacts and rationale of the study. It also elucidates the relevant knowledge it contributes to clean energy planning.

Several studies have explored modelling energy transitions and answering the questions of how nations could transform their overall energy sector to accommodate future changes in energy systems. These changes include high penetration of variable renewable energy. It is worth noting that the majority of studies have been carried out on developed nations known to have significant readily available data to explore their energy transition strategies. However, few studies have examined energy transitions from emerging economies and developing countries, especially from

the sub-Saharan African region where energy poverty looms, including clean cooking. Meanwhile, no study (to the knowledge of the author) has investigated energy transition from the perspective of stakeholders that investigates how the roles, opinions, and perspectives of stakeholders in the energy sector translate into energy modelling assumptions that provide succor for clean energy policy implementation. The clean energy assumptions obtained from stakeholders' analysis could then translate into policy scenarios used to explore and plan a nation's net-zero emission targets and achieve energy security.

Several energy systems modelling tools have recently gained the attention of energy system planners in industrialized countries. These tools are used to model nations' energy transition and evolution. A few commercial energy modelling tools have been widely used to model developing countries' energy transition paradigms. These could be attributed to the tool's incompatibility with developing countries' asymmetrical energy system settings. This represents the poor developing countries' energy reality, and other reasons were earlier explained. In addition, they have not followed the U4RIA guidelines for energy system modelling. Open-source tools could support clean energy planning for developing countries. Open-source tools have been proven to follow the U4RIA model principle. Therefore, the current study conducts a suitability and compatibility assessment of open-source modelling in the framework of developing countries' energy systems, economic architecture, and large energy demand gaps. The study also employs the most compatible open-source tools to create energy transition scenarios and pathways to investigate net-zero emission strategies and carbon neutrality in the energy transition framework of a typical emerging country. While this approach is novel, it contributes to the existing body of knowledge in planning a developing country's clean energy paradigm.

The current study has provided substantial knowledge of stakeholders' perspectives on energy transition as a main driver of clean energy development and planning. Additionally, it has contributed to the development of new knowledge in the field of net-zero emissions planning, energy system modelling (including energy efficiency) and clean cooking, and the paradigm of clean energy planning in developing countries as well; more so, this is exemplified in the Nigerian power sector. Besides, the study explored an excellent standard of how energy policy could be translated into modelling assumptions for long-term policy insights.

The results of the study would be of significant benefit to practitioners in research, development, and academia. They include but are not limited to technicians, scientists and engineers. Likewise,

policymakers, energy planners, investors in clean energy, and the association of energy users will benefit from the study outcome. Also, the immediate society and the community of energy practitioners will benefit immensely from the study. It will also enlighten practitioners on how to translate energy policy into modelling assumptions. This will give insights into the evolution of clean energy development in the future, especially in emerging economies.

Lastly, it is worth stating that no study has painstakingly explored the dynamics of the Nigerian low-carbon energy transition from the perspective of stakeholders while considering its net-zero transition agenda in its overall framework. In addition, addressing the challenges from an energy-economic-environment (3Es) perspective becomes essential. Therefore, the study is applied and used to model and investigate the Nigerian energy sector for transition to a low-carbon future, by examining the role of energy technologies mix, economic, and environmental based stakeholder perspectives.

1.7. Research Limitation

The limitations of this study are based on: (i) exploring stakeholders' perspectives, and (ii) analyzing assumptions and scenarios derived from stakeholders' perspectives.

First, stakeholders' perceptions of the Nigerian energy transition agenda were assessed as ways the proposed transition framework could be realized. Stakeholders' opinions and perceptions are critical to energy transition; it is thus worthwhile to mention that they could over or underestimate the transition process and the complexities involved. Consequently, future studies could assess complex dynamics using stakeholders' views, which would examine how current energy challenges in Nigeria could influence energy transitions' temporal scale. More specifically, the current study only considers stakeholder perspectives on transitioning to clean energy. It focuses on the power and cooking sectors but no evidence on the transportation sector. Though the power sector needs significant reform and transition to modern electricity, other sectors where it has direct or indirect impacts are transportation, oil and natural gas. Therefore, these sectors are to be investigated.

Second, we explored stakeholders' perspectives concerning four thematic trends, including (i) energy transition and its motivation, (ii) information/knowledge about energy transitions, (iii) technology that could shape this transition, and (iv) perceptions due to finance. In reality, other thematic factors (e.g., market dynamics, socio-economic, and techno-economic factors) can

influence energy transition beyond the thematic areas considered here. This implies that there is room for further analysis of the Nigerian energy transition considering these thematic areas.

Third, clean cooking analysis has mainly focused on the base and diffusion theory. Variables such as household size, income, price and information have been considered in the model. However, other factors are responsible for spreading clean cooking in developing countries. As a statistical inferential approach, the methodology may not be compatible with the study. In terms of data, the study uses secondary data, though it is based on primary data.

1.8. Outline of Research Structure

The rest of this study is organized as follows: Chapter Two details the stakeholder's perspective and energy transitions in developing countries while elaborating on research analysis on the dynamics of low-carbon transitions in Nigeria from the stakeholders' perspective. Chapter Three explores the compatibility assessment of open-source energy models and details the application of open-source energy models to exploring low-carbon energy development, gleaned policy insight from stakeholders' opinions analysis. It investigates how policy insights could be translated into modelling assumptions for Net-zero energy transition plans. Chapter Four investigates energy planning from an energy-distributed viewpoint gleaned from the analysis of stakeholders' views and compatibility assessment of the open-source model. Energy transition to clean cooking will be explored in Chapter Five which presents a low-carbon development and policy implication for developing countries. Finally, Chapter Six discusses the implications of the overall study investigation and offers some perspectives for future research.

CHAPTER TWO

STAKEHOLDER'S PERSPECTIVE AND CLEAN ENERGY DEVELOPMENT

2.0. Introduction

Global warming (GW) is threatening our existence on Earth. To date, every region has experienced diverse challenges due to global warming caused by increasing anthropogenic carbon dioxide emissions (NASA, 2021). Globally, about 65% of carbon dioxide (CO₂) emissions are due to fossil fuel use, a dynamic shift to clean energy sources is pertinent to curb the continued emissions of CO₂ (IPCC, 2014). Transitioning from fossil fuel to a cleaner energy paradigm requires reliable and ambitious measures by nations to cut greenhouse gas (GHG) emissions and enhance the security of their respective energy systems. As such, several governments have pledged their commitments to limit their emissions (Parry, 2015). While most developed economies are committed to cutting down their GHG emissions, some developing countries are concerned about ensuring the security of the energy supply (IRENA, 2017). Meanwhile, a three- to five-fold increase in electricity demand is projected in developing countries over the next 30 years (Ahuja & Tatsutani, 2009). This increasing energy demand will be met by fossil fuel resources if a deliberate clean energy future driven by decarbonization of the power sector is not prioritized (Fankhauser & Jotzo, 2017). Therefore, it is opined that emerging economies fully harness the economic prosperity that comes with low-carbon development.

It is worth noting that planning a low-carbon energy future is one of the prerequisites to limiting GHG emissions that may have the potential to cause a rise in global average temperature. Such planning is pertinent in the energy sector because fossil-led economies are depleting (OPEC, 2016) and constitute critical environmental and health challenges through indoor and outdoor air pollution (Manisalidis *et al.*, 2020). Furthermore, large hydropower plants are increasingly threatened by shrinking rivers, thereby shaking the security of electricity supplies in countries dependent on hydropower (Kaunda *et al.*, 2012).

Several studies have explored thematic areas of the energy transition, including perspectives of energy transitions (Khalilpour, 2018; Schreurs, 2020), including international reports (OECD/IEA & IRENA, 2017; IEA, 2017a; IEA, 2023). For example, Doran *et al.* (2022) examined how people perceived societal low-carbon transition and its possible pathways, concerning energy production

and use. Solar, wind and hydro were perceived to be more effective for mitigating the impact of climate change, whereas energy production from nuclear was perceived to have no mitigating impact. Also, Sorman et al., (Sorman *et al.*, 2020) examine expert stakeholders that guide future energy insights on low-carbon transitions in Spain.

Emerging economies have committed to cutting down emissions in their Nationally Determined Contributions (NDCs). However, these nations struggle to meet low-carbon commitments made in their respective NDCs (UNDP, 2016). In the case of Nigeria, the government has pledged in her NDCs to reduce its emissions by 20% by 2030, when compared to business-as-usual levels (NDC, 2021b). The GHG emissions have been consistently rising with about a 271% increase since 1990 (shown in Figure 2.1) and were the 17th biggest (2nd in Africa) after South Africa (Hansen, 2020). There is indeed a need to abate greenhouse gas (GHG) emissions in Nigeria for both economic prosperity and social well-being.

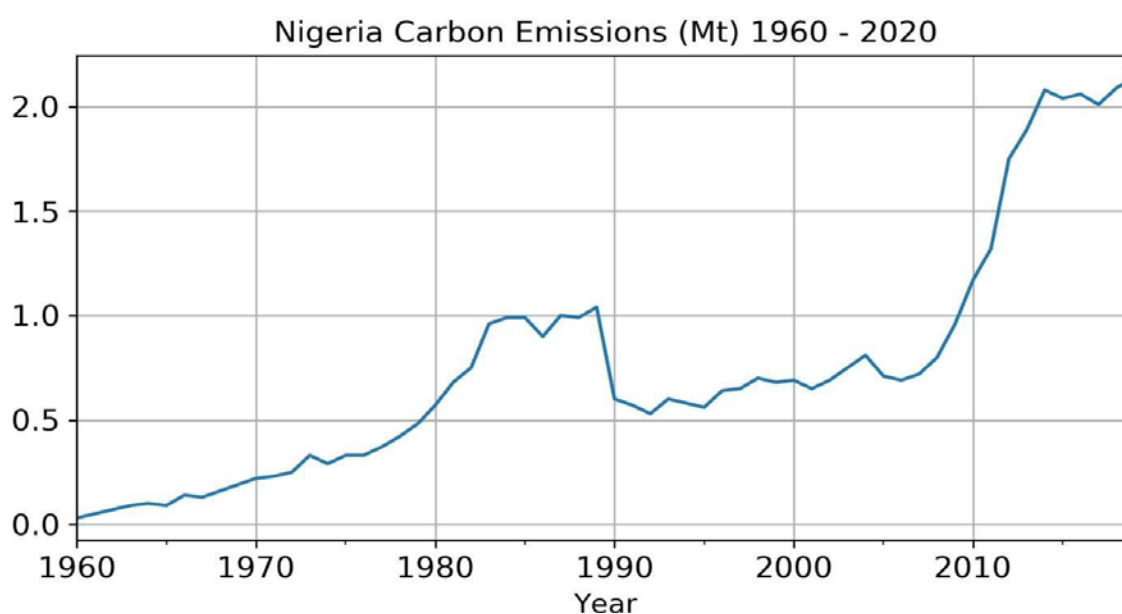


Figure 2. 1. Carbon emissions in Nigeria from 1960 to 2020. (Data source: TealTool, 2021)

In addition, a silent crisis is unfolding in developing countries like Nigeria, where about 85 million of its population live without access to electricity (World Bank, 2021). This shortage makes the residents heavily dependent on wood, which has remained scarce and over-exploited, thus making more vulnerable the poor and endangering efforts to reduce poverty, thereby making Nigeria the country with the largest energy access deficit in the world (World Bank, 2021). Transitioning to clean energy tends to improve and bridge the country's existing energy gap and deficit (World

Bank, 2021). This transition to a low-carbon energy system is not simply a matter of replacing polluting electricity sources with renewables, but rather creating new power systems that enhance energy security, based on efficient, renewable, flexible and decentralized (including off-grid) infrastructure, thus preventing a situation in which growing demand is met with fossil fuel sources (IRENA, 2021; J. Li & Jiang, 2019).

To achieve a successful penetration of clean energy in Nigeria, the government 2005 developed a medium to long-term plan to gradually phase out crude oil. In the medium term, Nigeria envisions an energy transition from crude oil to a less carbon-intensive economy, increasingly powered by natural gas (The Guardian, 2021). The impact of renewable energy on the national energy supply was also forecasted to be felt in the medium term. In the long term, the country's total dependence on hydrocarbons was envisioned to decrease significantly. Moreover, the plan was updated in 2011. It sought to increase the quota of renewable electricity by 13%, 23%, and 36%, respectively, in 2015, 2025, and 2030. In contrast, IEA and IRENA projected renewable energy to account for about 10% of the Nigerian total energy consumption by 2025 (IEA/IRENA, 2013). Unfortunately, fifteen years after, the growth, exploration, and utilization of renewable energy have not been significantly felt. Currently, the share of renewable energy in total electricity consumption is still marginal (Ojo *et al.*, 2020).

Furthermore, despite a series of policy frameworks, laws, regulations, legislation, standards, policies, strategies, and plans to propel national low-carbon development, little impact on clean energy has been achieved in attaining the needed energy security. Achieving a low-carbon energy agenda in Nigeria could have been hampered by a lack of robust and proper stakeholders' involvement in the short-, medium-, and long-term planning processes (OECD/IEA/NEA/ITF, 2015). According to Yawson & Greiman (Yawson & Greiman, 2014), there is a need to conduct a stakeholder analysis that is aimed at gleaning vital information essential to planning a low-carbon energy future at the national level. Eventually, a well-planned low-carbon energy sector would enable the successful realization of the nation's strategies and plan. Consequently, scholars recommend that stakeholder analysis be both a tool and approach to understanding the preferences and views of experts on a subject matter and enhancing communication between researchers and policymakers (Balane *et al.*, 2020).

Consequently, using a multi-stakeholder analysis, the current study applied an interactive approach to consolidate low-carbon energy planning and facilitate Nigeria's energy transition. Thus, the approach was designed to capture technology uncertainties and complexities in finance innovation that are peculiar to developing clean energy portfolios in emerging economies. In light of this, the study explores the dynamics of stakeholders' perspectives toward planning a low-carbon energy future of the Nigerian power sector. Hence, the study adopts a systematic and descriptive statistical approach to analyze stakeholders' views in the context of low-carbon energy planning.

The rest of this chapter is organized as follows: Section 2 details the theoretical and conceptual framework, section 3 sets out the methodology which elucidates techniques used to explore the dynamics of stakeholder analysis, section 4 provides findings from the analysis of data, and Section 5 discusses the implication of this investigation, while section 6 concludes the study with some policy implication.

2.1. Concept of Stakeholder Theory and Motivation for an Energy Transition

This sub-section describes the state of the art of stakeholder theory and its contributory perspective to clean energy development, its motivation, and progress beyond.

In the context of energy insecurity and the global climate crisis, the sustainable development of clean energy has become a relevant task for future energy development. Clean energy development requires a significant shift in the overall energy outlook of a nation from the supply side to its demand side management. Stakeholders play a crucial role in influencing tasks relevant to the energy transition. Therefore, engaging stakeholders and understanding how feedback could exist among them could help energy planners to properly decipher environmental, social, political, economic and technological factors to enhance transparent and timely low-carbon transition processes. Although, most developing countries lack the necessary infrastructure, data, political will and synergy, finance and technology to achieve a timely and transparent low-carbon development. It is therefore apparent that achieving energy transition in most emerging nations could be delayed as low-carbon transition pathways entail diverse uncertainties and risks. Consequently, it is imperative to delineate the concept of stakeholder theory as it facilitates or thwarts the low-carbon energy development agenda, especially in emerging economies.

The concept of stakeholder is broad; however, its usage is dependent on the context, research framework and the value that stakeholders can create (Franklin, 2020). Considering the complex nature of defining stakeholder theory and motivation, Franklin proposes a system dynamics approach for making theories of stakeholder motivation. In a similar view, stakeholder engagement should be strategically inclusive, while considering the following stakeholders' values: representative, transparent, accessible, responsive, and accountable. When the aforementioned values are holistically and critically achieved given stakeholder analysis it will result in a sustainable policy (Skordoulis *et al.*, 2020).

According to Schmeer (2000), a stakeholder is any entity/organization or actor with a declared or conceivable interest or stake in a promoted policy. Stakeholder analysis is, therefore, both an approach and a tool (Varvasovszky, 2000; Zsuzsa, Varvasovszky & Ruairi, 2000). It aims at generating knowledge about an actor's preference on a subject matter for policy implication (Mulyaningrum *et al.*, 2013). The Stakeholder analysis approach employed in this section allows scientists to interact effectively with key stakeholders and to know their support and interest in sharing their opinions on energy transition policy and related programs. The conduct of stakeholder analysis could allow for the proper alignment of government policies in such a manner that prevents potential misunderstandings and misinterpretations during implementation (Edomah *et al.*, 2020). This procedure implies that when stakeholder analysis is conducted early, policy implementation processes such as matters about energy transition are more likely to succeed (Yawson & Greiman, 2015).

Several studies have explored significant ways of enhancing robust policy and implementation through stakeholder analysis (Doran *et al.*, 2022; Balane *et al.*, 2020; Varvasovszky, 2000). They generally concluded that while analyzing stakeholder preference it is important to understand their values, interests and preferences. As such, the policy would be evaluated to assess its sustainability after implementation.

In light of that, Balane *et al.* (2020) applied stakeholder analysis to develop a framework that contributes to policy implementation research by offering practical tools for analyzing the characteristics of actors in the health sector and also policymaking in defining the legality of lumbering in the private forest (Mulyaningrum *et al.*, 2013). The work of Pizarro-irizar *et al.* (2020) conducted a stakeholder analysis that assessed their perspectives on low-carbon energy transitions. Their study employed an approach of quantitative data collection via an online survey and

stakeholders' engagement to identify barriers between stakeholders and scientists concerning climate change mitigation actions. In addition, Results from their study revealed that there is a need for more communication between stakeholders and modellers (scientists). Similarly, Wijk (2021) assessed the acceleration of energy transition in the Dutch power sector, from the perspective of a utility power company in collaboration with their stakeholders, by creating stakeholder values using the stakeholder theory. After that, a robust understanding was established through a shared purpose between the power company and the stakeholders. Also, stakeholder theory was applied to assess the adoption of solar energy technology in Lebanon, focusing on the socio-cultural dimension. The study revealed that social, cultural, geographic, and market dimensions played a crucial role in the uptake of solar energy technology by different consumer groups (Elmustapha *et al.*, 2018). In a similar light, Sovacool (2016) examines the temporal scale of the energy transition on a global and national scale. Sovacool found that the timing of energy transition may not always be supported by empirical evidence. Sovacool, therefore, argues that a more holistic approach and transparent conception to assessing energy transitions should be considered.

To achieve a holistic analysis of national energy transition, the current study has applied approaches and tools of stakeholder analysis 'transparent conception' outlined by (Varvasovszky, 2000; Yawson & Greiman, 2015; Zsuzsa, Varvasovszky & Ruairi, 2000) and considered a systemic approach – "feedback approach," thus making current study novel (Sovacool, 2016). This approach, therefore, enhances the credibility of the study by exploring the dynamics of stakeholders' preferences via a system thinking method. System thinking found its background application in system dynamics, where a causal loop diagram is employed to understand interactions and feedback loops between relevant variables (Sterman, 2000; Shari *et al.*, 2020; Shari & Moumouni, 2020).

2.2. Conceptual Framework of the Study

A systemic approach was utilized to design a conceptual framework for this research. The systemic approach is part of the system thinking conceptual framework (Banson, 2016), which qualitatively explains the study objectives, i.e., stakeholders' perspective on energy planning and a national low-carbon energy transitions agenda. The conceptual framework elucidates the (i) methodology and (ii) theoretical/conceptual framework to design a methodological background for the study. Figure 2.2 shows a framework that has informed the orientation of the current study.

According to Figure 2.2, the study has evolved through five-phase steps, including:

- i. Research perspective and agenda: stakeholders' engagement, views, drivers, and opinions,
- ii. Data (primary data), which includes quantitative and qualitative data,
- iii. Surveys in the form of structured interviews and online & real-time questionnaires,
- iv. Analyses that are statistical and qualitative based on system thinking; see ((Sterman, 2000), (Maani & Maharaj, 2004), (Shari *et al.*, 2020b; Shari & Moumouni, 2020)) for more details, and
- v. Policy implication on planning a low-carbon energy future.

The innovative aspect of this work is the perspective and plan that informed the stakeholder engagement study. We carried out that initiative through a two-way survey, i.e., combined online and real-time hardcopy questionnaires, alongside some structured interviews with decision-making stakeholders and non-decision-making stakeholders in the electricity sector (Edomah *et al.*, 2021b).

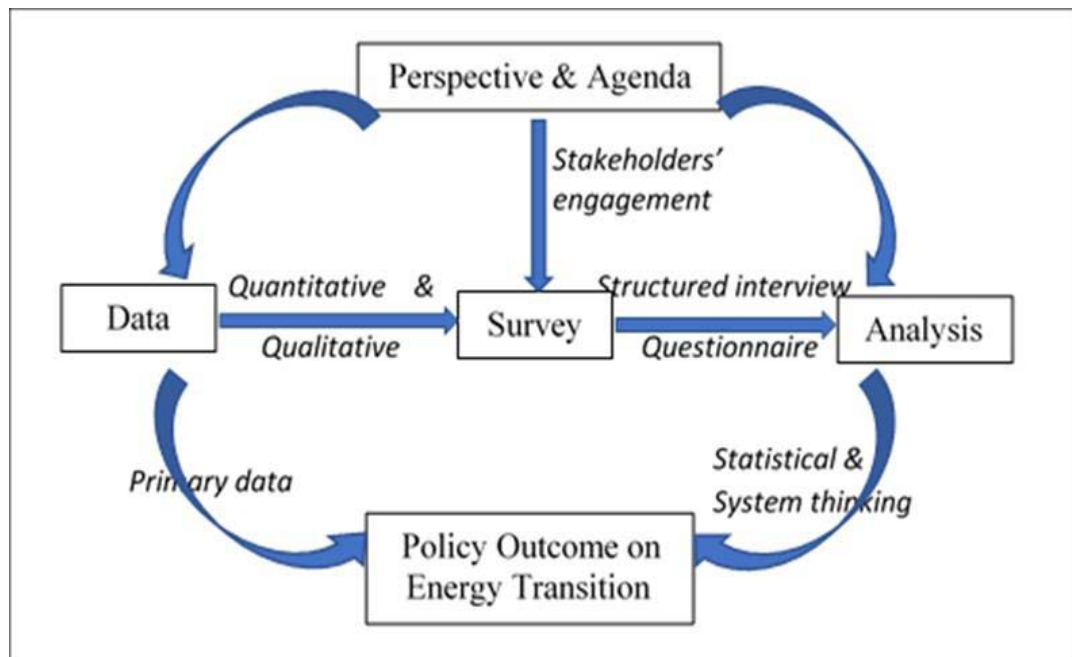


Figure 2. 2. Conceptual framework of the study

Furthermore, Figure 2.2 shows the endpoint of the stakeholder's assessment which is the develop a policy outcome for the energy transition. The outcome of the energy transition would suggest the uncertainty and risk in underlying environmental, social, political, economic and technological

factors of Nigeria's energy transition, especially its low-carbon development in the power sector. Also, transitioning to a cleaner energy system is strongly dependent on temporal variation, including short-, medium- and long-term plans. Energy transition outcomes should identify these variations.

2.3. Study Research Design

This section presents information concerning the research design, data type, data collection, and data analysis for the case of planning a low-carbon energy future from the viewpoint of relevant stakeholders in the Nigerian power sector.

In this study, special attention was paid to the views and perspectives of relevant stakeholders in the power sector. A mixed methodology was employed to assess their viewpoints: a structured survey approach using stakeholder interviews for qualitative data and a questionnaire for quantitative data (Pizarro-irizar *et al.*, 2020). The theoretical approach employed enables us to gain insight from existing literature (Elmustapha *et al.*, 2018). On the one hand, information feedback was employed to show relationships and patterns observed in the qualitative survey, to understand the information feedback that explains causal relationships among stakeholders' opinions towards planning a low-carbon energy future in Nigeria. On the other hand, quantitative data collected via questionnaire survey were analyzed using a statistical approach in IBM SPSS and R software (SPSS, 2020 and Harris, 2018).

To achieve the goals of the study, the questionnaire investigated four main criteria:

- i. Mapping stakeholders and their core motivations,
- ii. Informing about low-carbon energy transitions,
- iii. Technology options and preferences, and finally
- iv. Issues concerning national energy transition and financial innovation.

Additionally, the stakeholders' interviews explored three thematic issues of energy transitions:

- i. Personal experience with energy transitions,
- ii. Energy transitions and its concerns, and
- iii. Finances and economies of energy transitions.

Figure 2.3 presents the framework that governs the survey. Furthermore, this figure illustrates the interrelationships between data collected via questionnaires and interviews. It is also worth noting that information captured with the use of questionnaires was closed-ended. As such, it might not

reveal information related to some uncertainties and dynamic patterns of the study. This fact was made up for in the interview, according to (Nayak & Narayan, 2019). Outcomes would thereby map relevant uncertainties of low-carbon energy transitions.

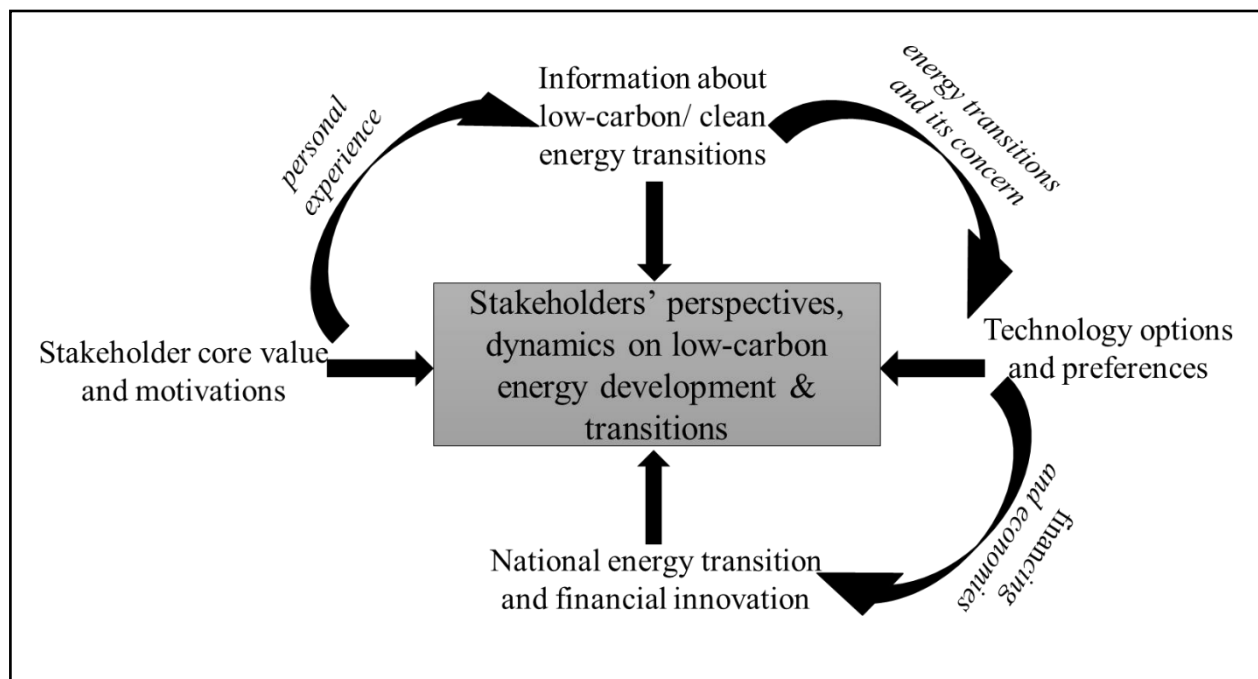


Figure 2. 3. Framework approach to survey data collection

2.3.1. Data

The surveys have considered various protocols due to the COVID-19 pandemic, and the peculiarity of the Nigerian workplace, such as limited stakeholders' time, work-from-home (WFH) policy, and available resources. As a result, the questionnaire was concisely designed, and interview sessions were done with appropriate permission. Besides, it is important to state that stakeholders in the power sector were identified and not selected at random, but the selection was made based on guidance from the National Energy Master Plan (ECN, 2018).

The limited schedule of respondents informed the snowball sampling technique during the survey process (Dragan & Isaic-Maniu, 2013). According to Table 2.1, respondents and their affiliations were carefully selected among the following: i) government (46.9%); ii) service providers (19.4%); iii) regulators (4.1%); iv) financial actors (5.1%); v) science, academia, and research institutes (14.3%); and vi) others (10.2%), which includes inter-government organizations, consumers, associations, trade unions and workers, advisors, civil societies, and media. The respondents cut across local, national, and international parastatals. The approach remains helpful in illustrating

how the views of stakeholders can be incorporated into the planning of a low-carbon energy transition. These selections, therefore, captured the stakeholders' core motivation in the questionnaire. Furthermore, observation research – more structured and less structured - was conducted to guide the collection of quantitative and qualitative data, respectively. This scheme is in line with Sapsford & Jupp (Sapsford & Jupp, 1996).

Table 2. 1. Affiliations of the stakeholders (%)

Affiliation	Percentage
Governments	46.9%
Service providers	19.4%
Regulators	4.1%
Financial actors	5.1%
Science, academia, and research institutes	14.3%
Others	10.2%
Total	100%

The selected stakeholders were consulted during stakeholders' and policy review conferences, meetings, and workshops organized by the Energy Commission of Nigeria (ECN) between November 2020 and July 2021. About 150 samples of the questionnaire were administered during those mentioned energy policy conferences.

Furthermore, energy organizations/stakeholders such as the Electricity Consumer Associations not represented during the workshops were visited. Hence, the stakeholders answered about 45% of the administered questionnaires upon retrieval. In addition, an online survey via Google form was utilized to reach more stakeholders who would have been otherwise left behind. This strategy also allowed us to reach out to others who attended the multi-technical online events. About twenty-four (24) responses were obtained from the online survey, out of which 96% were relevant — making a total of 98 samples of questionnaires retrieved from physical and/or virtual surveys. However, of 98% of the recovered questionnaires, about 75% were obtained from in-person surveys, while 25% were online. In addition, several other interview sessions (online, calls, and face-to-face) were scheduled and conducted successfully. Three (3) comprehensive interview

sessions were granted and recorded. It is worth pointing out that special permissions were taken from each respondent before the recording took place.

In addition, stakeholder sampling biases that could ensue as a result of selection biases were circumvented by avoiding convenient sampling, that is authors have made a consistent effort to collect data and information from not only easily available and accessible respondents but also made a conscious effort to mobilize responses from the different subgroups that make up a particular group of interest, in the form of focused group discussion and interview. In addition, respondents who did not respond to the interview and questionnaire on time were politely informed and reminded. More importantly, the authors have carefully and systematically defined the target population for the survey, the parameters for sample selection, and the sampling frame of the study. These are represented in Table 2.1, and Figures 4 and 5, respectively.

The quantitative data were analyzed accordingly employing descriptive and inferential statistical approaches. Meanwhile, the Pearson correlation coefficient using the Pearson correlation formula shown in Equation 1 has been used for the inferential approach.

$$r = \rho (x, y) = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}} \quad (1)$$

Where r represents the correlation coefficient, $\rho (x, y)$ represents Pearson correlation of the independent variable x and independent variable, y ; x_i are the values of the x -variable in a sample; \bar{x} represents the mean of the x -variable; y_i are values of the y -variable in a sample; \bar{y} represents the mean of the y -variable. Results were systematically cross-checked for inconsistencies in the responses from respondents and any missing data. Afterwards, we coded the results with Microsoft Excel and Python. We then carried out meticulous checks for data consistency purposes. Recorded voice interviews were manually transcribed and coded. The data collection, debugging, cleaning, and analysis process was rigorous. Therefore, a preliminary understanding of the relationships and patterns was observed. These observations helped guide the analysis and result presentations.

2.4. Results

This section presents the main findings of the study. The outcome of the study is outlined as follows: (i) mapping stakeholders' core motivation and affiliation (section 4.1), (ii) response to stakeholders' perception of energy transitions such as low-carbon transitions and technology options & preference (section 4.2), and finally (iii) economies and finances of energy transition (section 4.3) using both descriptive and inferential statistical approaches.

2.4.1. Mapping of Stakeholders and their core motivations

This section presents the analysis of stakeholders' affiliations and their core motivations concerning the primary area of interest in clean energy projects. The transitions of the latter are equally covered in this section.

2.4.1.1. Primary areas of interest in the power sector

Figure 2.3 portrays eight primary areas of interest in stakeholders' engagement in the power sector; these include (i) policymaking, (ii) policy coordination, (iii) investment and finance, (iv) supply and electrification, (v) system operator, (vi) transmission and distribution, (vii) market operator, and (viii) research and development. Categorical variables assessed on the Likert scale, abbreviated as M – Most important, I – important, N – Neutral, L – less important, and Lt – least important, were utilized to categorize and investigate stakeholders' affiliations and priorities concerning their area of interest (see Figure 2.4).

According to the outcome of the stakeholder's primary area of interest represented in Figure 2.4, about 72.7% and 78.4% of government affiliates claimed that policymaking and policy coordination, respectively, are the essential areas of interest to their organizations. This perception indicates that affiliates from government parastatals have interests, ranging from Most Important (M) to Important (I), and are involved in all the core areas of interest in the power sector. Also, service providers claimed that the core area of interest is market operator (87.5%), transmission and distribution (91.7%), and system operator (80%).

Also, financial actors found the most relevance in investment and finance (25%) and were sometimes involved in policy coordination. Affiliates from science, academia, research institutes, and the government claimed that research and development are most important. In contrast, "others" show no significant interest in research and development (R&D), policy coordination, and

system operator, their indifference to research and development could be due to the stakeholders' role in the organization, limited scope, view and understanding of the Country's energy transition development agenda. Overall, this implies that stakeholders in the power sector have mixed and overlapping interests, as shown in Figure 2.4.

Considering the stakeholders' involvement in multiple clean energy projects as presented in Figure 2.5, about 88.8% of the respondents claimed to be involved in one or more clean energy projects. Of these proportions, advocacy and innovative renewable energy and energy efficiency projects are the most executed tasks, with 76.5% of the respondents in clean projects. In comparison, R&D (72.4%) is the second most executed project among the respondents. In addition, fewer stakeholders' have performed projects related to investments in clean cookstoves (44.9%). It is worth noting that the various respondents engaged in other pilot projects, such as the following:

- i. renewable technologies (solar panels, mini-grid, biofuel refinery, etc.),
- ii. design and construction of hydropower plant,
- iii. training awareness and capacity building, and
- iv. nuclear technologies.

The above-mentioned were areas of clean energy projects that respondents undertook with a 13.2% proportion of the total claimed clean energy projects.

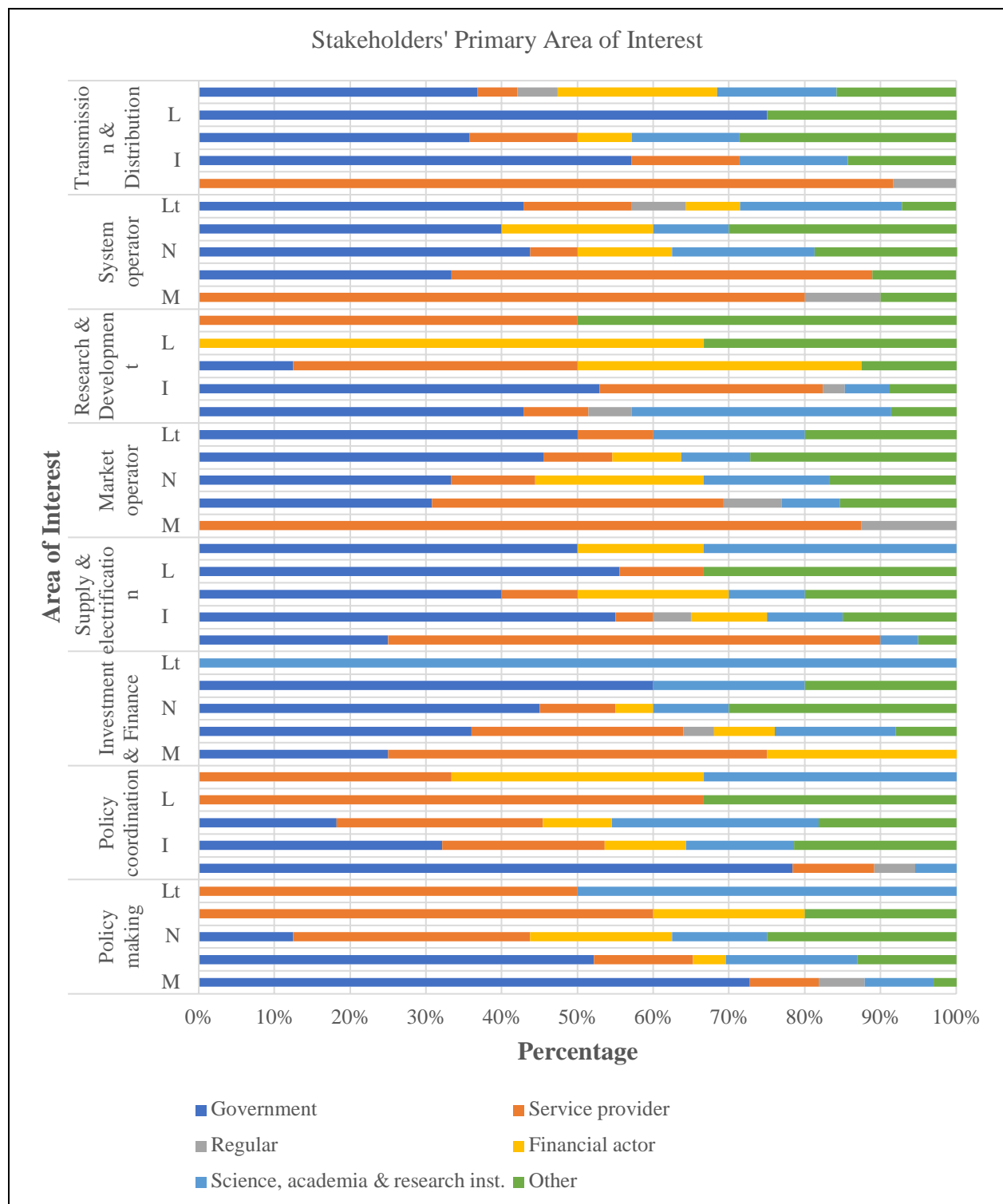


Figure 2. 4. Stakeholders' area of interest in the power sector

Concerning the involvement of stakeholders at different stages of the development of energy projects, affiliates from the government are always involved in one or more of the early stages (conception, planning, design, and feasibility studies), development/deliberation stages, funding, evaluation, and monitoring. Service operators claimed to be often involved in the implementation/operation stage of clean energy projects. Compared to the government's affiliates, service providers are constantly engaged in the execution and communication stage of energy projects.

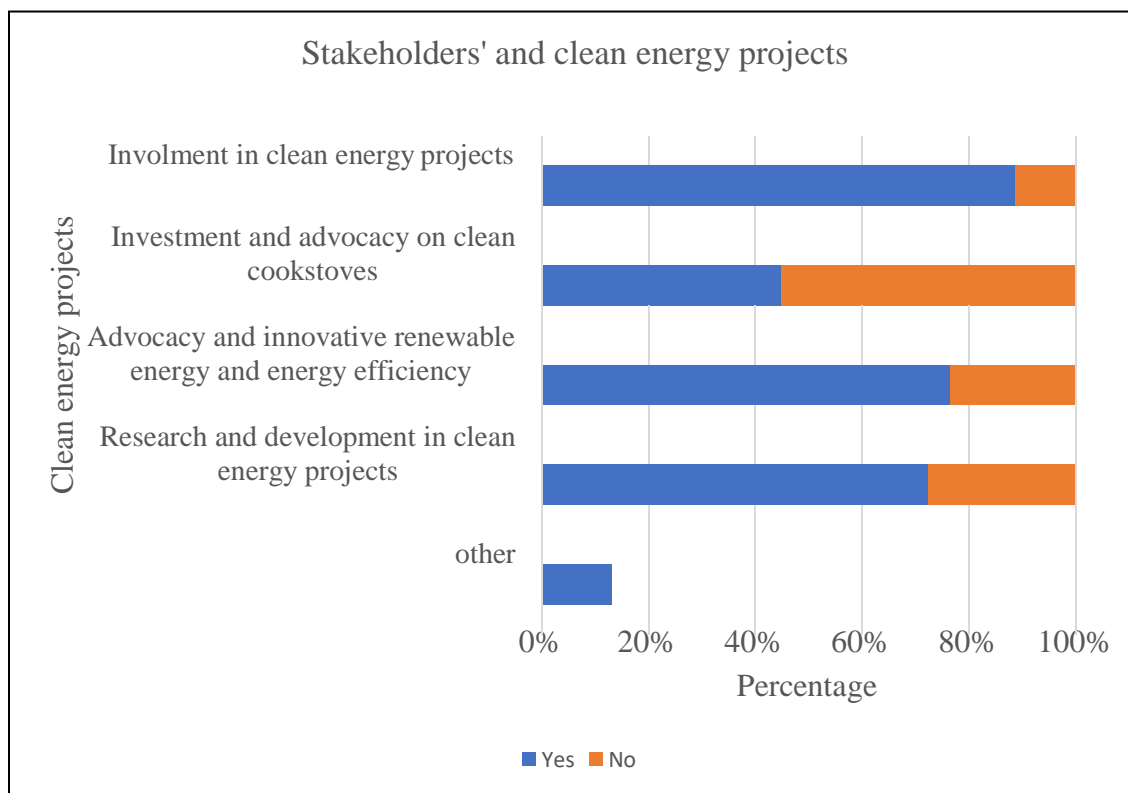


Figure 2. 5. Stakeholders' involvement in clean energy projects.

2.4.2. Perceptions of Stakeholders on Energy Transitions

This subsection assessed stakeholders' views and tasks concerning energy transition and presented the results of the survey by outlining stakeholders' opinions on information about energy transition, technical and behavioural requirements, and financial innovation options towards planning a low-carbon future.

2.4.2.1. Information about low-carbon energy transition

To sample the opinion of stakeholders and the level of how informed they are about the energy

transition stakeholders' analysis has proven that: all respondents claimed to be aware of the concept of the energy transition. Also, to affirm the claim, about 75.5% of the respondents asserted to be mindful of the international treaty on climate change – the Paris Agreement. In addition, about 91.8% of the respondents affirmed that the energy transition is a significant structural shift in the energy sector from fossil fuel-based energy production systems to renewable energy sources. This implies that most of the respondents are aware and familiar with the concepts, and implications of energy transitions.

The results show that about 69.4% of respondents claimed that the Nigerian energy system had not undergone significant structural changes in its power sector regarding low-carbon transitions. Meanwhile, about 56.1% of respondents have not been involved in low-carbon/clean energy training for the power sector. The dependency on fossil fuel is still significant at about 67.3%, and the respondents consented that reliance on fossil fuel is not fading out any soon in the Nigerian energy space. This could result from Nigeria's heavy dependence on fossil fuels for electricity generation in the form of captive/self-electricity generation from diesel-powered generators. Because of the dependency on fossil fuels, respondents suggested the need to increase advocacy about low-carbon development and include it in the nation's education curriculum across all levels. As such, about 92.9% of respondents claim that the concept of a low-carbon energy future in the nation's academic curriculum to enhance advocacy would promote clean energy.

To further affirm respondents' perception of the energy transition, Table 2.2 presents descriptive statistics of the five-point Likert scale on stakeholders' opinions regarding the most critical task of energy transitions. On the five Likert scales, the mean is considered on an interval of 1 to 1.8, which means "least important"; 1.81 to 2.60, meaning "less important"; 2.61 to 3.40, meaning "neutral"; 3.41 to 4.20, meaning "important"; and finally, 4.21 to 5, which stands for "most important."

According to Table 2.2, most respondents considered sustainability in all its ramifications as the essential task of the energy transition, shown by a mean of 4.56. Also, respondents agreed that developing energy efficiency standards is a crucial task in the energy transition. Furthermore, the respondents claimed that capacity building alongside gaining knowledge of clean energy is another important task of the energy transition. More so, more respondents have considered the development of clean energy policies as the most significant task of the energy transition with a

mean of 4.59.

In addition, Table 2.2 affirms that advocacy makes others aware of the importance of energy transition and gaining more knowledge about the energy transition. These are the most relevant tasks to be prioritized in achieving a low-carbon energy future. However, developing an appropriate clean energy policy takes prominence among the tasks considered.

Table 2. 2. Descriptive statistics on relevant tasks that describe energy transition

	N	Minimum	Maximum	Mean	Std. Deviation
Sustaining in every way possible	93	2	5	4.56	.598
Develop energy efficiency standards	93	2	5	4.52	.653
Making others aware of the importance of energy transition	94	2	5	4.48	.582
Gaining more Knowledge of the topic	94	3	5	4.39	.513
Implementing a Clean Energy Agenda	94	3	5	4.50	.600
Develop a clean energy policy	95	1	5	4.59	.644
Valid N	90				

Note: 5- most important, 4- important, 3- neutral, 2- less important, 1- least important.

To further confirm the outcomes from Table 2.2, relevant and actionable concepts that would boost the achievement of a low-carbon energy future are presented as the mean on a five-point Likert scale in Table 2.3. Most respondents agreed that sustainability, affordability, reliability, safety, power infrastructure, and feasibility are critical in achieving low-carbon development. Nonetheless, the majority (according to the mean) of respondents have claimed that achieving a sustainable low-carbon energy future is the most relevant agenda of energy transitions. At the same time, affordability is rated as the second (mean 4.61) most crucial concept in energy transitions. Furthermore, respondents acknowledged that smart grid systems and decentralization are also important to achieving a low-carbon future. This fact implies that affordable clean energy is crucial in attaining energy transitions, which is likely going to come through decentralized and smart grid systems. In contrast, respondents were neutral to the idea of a central utility grid system (the mean was 3.26).

Table 2. 3. Descriptive statistics on the relevant concept to drive a low-carbon energy future for a successful energy transition.

	N	Minimu m	Maximu m	Mean	Std. Deviation
Affordability	96	3	5	4.61	.550
Reliability	96	2	5	4.59	.573
Sustainability	96	3	5	4.65	.523
Feasibility	93	2	5	4.34	.634
Safety	95	3	5	4.52	.650
Decentralization (off- grid)	96	2	5	4.07	.849
Central utility grid system	91	1	5	3.26	1.094
Smart grid system	94	2	5	4.10	.791
Power infrastructure	92	2	5	4.40	.712
Valid N	85				

Note. 5- most important, 4- important, 3- neutral, 2- less important, 1- least important

We further carried out an analysis as shown in Table 2.4; respondents reaffirmed that advocacy of clean energy and investment in climate change would enhance low-carbon development. The outcomes (Table 2.4) also showed that energy-efficient products and human behaviour are important and play significant roles in achieving sustainable energy transitions. In addition, respondents claimed that transitioning to clean energy was a possible solution that could bring about economic prosperity by meeting electricity demand.

Table 2. 4.Descriptive statistics on the relevant concept to drive a low-carbon energy future.

	N	Minimu m	Maxim um	Mean	Std. Deviation
The energy transition is an important subject, which should get attention in my environment.	97	3	5	4.71	.499
The government should take measures against global warming, not the Nigerian residents.	96	1	5	3.26	1.275
Transitioning to cleaner energy is a possible solution to the power supply-demand gap and brings about economic prosperity.	96	2	5	4.11	.832

2.4.3. Technology options and preferences

To achieve the sustainable development goal seven (7) by 2030 and the African Union (AU) agenda on energy access and clean transition by 2063, it remains vital that stakeholders lead the way and collectively act now. Hence, Figure 2.6 shows stakeholders' preferences on potential technologies necessary for achieving SDGs 7 and the AU agenda. More respondents have considered solar photovoltaic (77.1%) and energy efficiency (62.8%) as the two most critical technological approaches in the short-medium (2030) and long-term (2063). In contrast, less than 2% of respondents considered coal an essential and/or important technology; this could be due to the adverse contribution of coal to the environment. In a bid to consider technology that could make

coal cleaner, respondents were neutral to carbon capture and storage (CCS) as a technology. Also, only about 21.6% of respondents considered CCS as necessary (Figure 2.6). This state of mind could be due to the current state-of-the-art and technical know-how about CCS technology. For other technologies (not stated in the survey), over 60% of those who selected other technologies have considered nuclear as part of the future clean energy mix, implying that nuclear might gain future relevancy and attention among low-carbon future technology mix in Nigeria.

Considering climate change mitigation and investment, about 84.5%, 69.6%, in that order, of respondents, have shown support for solar energy and energy efficiency as the most important means (see Figure 2.7) that should attract support, investment, and prioritization. Respondents also considered storage (45%) and green hydrogen (40.3%) important, while they claimed that coal and CCS technologies should receive minor support in terms of investment in climate change mitigation.

Figure 2.8 shows the evolution of technology as Nigeria transits to a low-carbon. Analysis indicates that energy efficiency technology, solar technology, wind, and hydropower would expand relative to coal which is likely to phase out. However, respondents claimed that natural gas (NG) is expected to grow in the next 30 years for both fuel and technology. This growth could be attributable to the low-carbon content nature of NG, the developed technology of NG exploration, and the nation's commitment to its utilization for cooking and as a substitute fuel for automobiles.

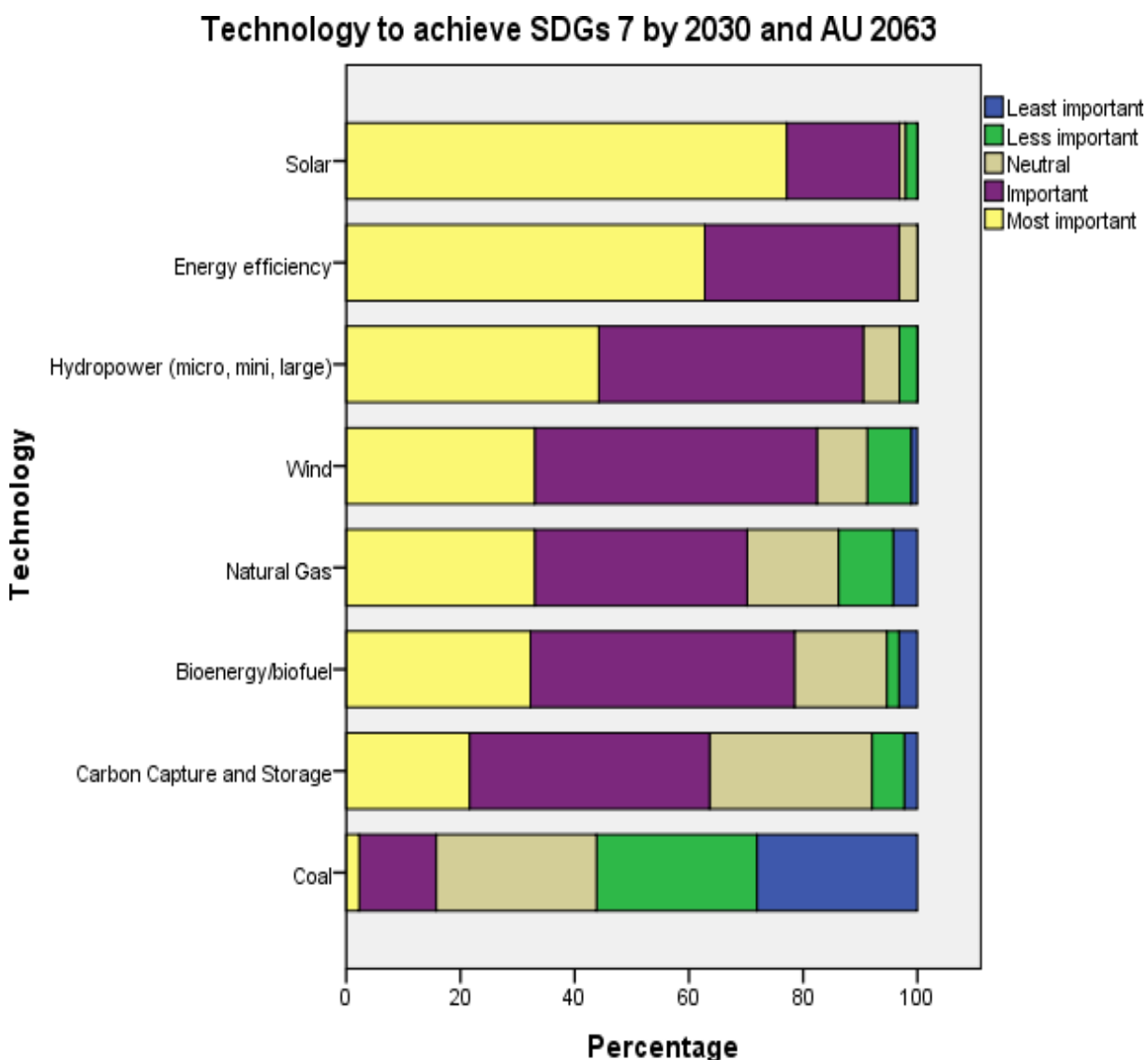


Figure 2. 6. Required technology to achieve SDGs 7 (2030) and AU 2063.

Lastly, considering stakeholders' perspectives, technologies that should be of interest and are likely to drive Nigeria's low-carbon future are solar energy (solar photovoltaic) and energy efficiency. These choices of technologies are also emphasized in the Nigerian Energy Master Plan.

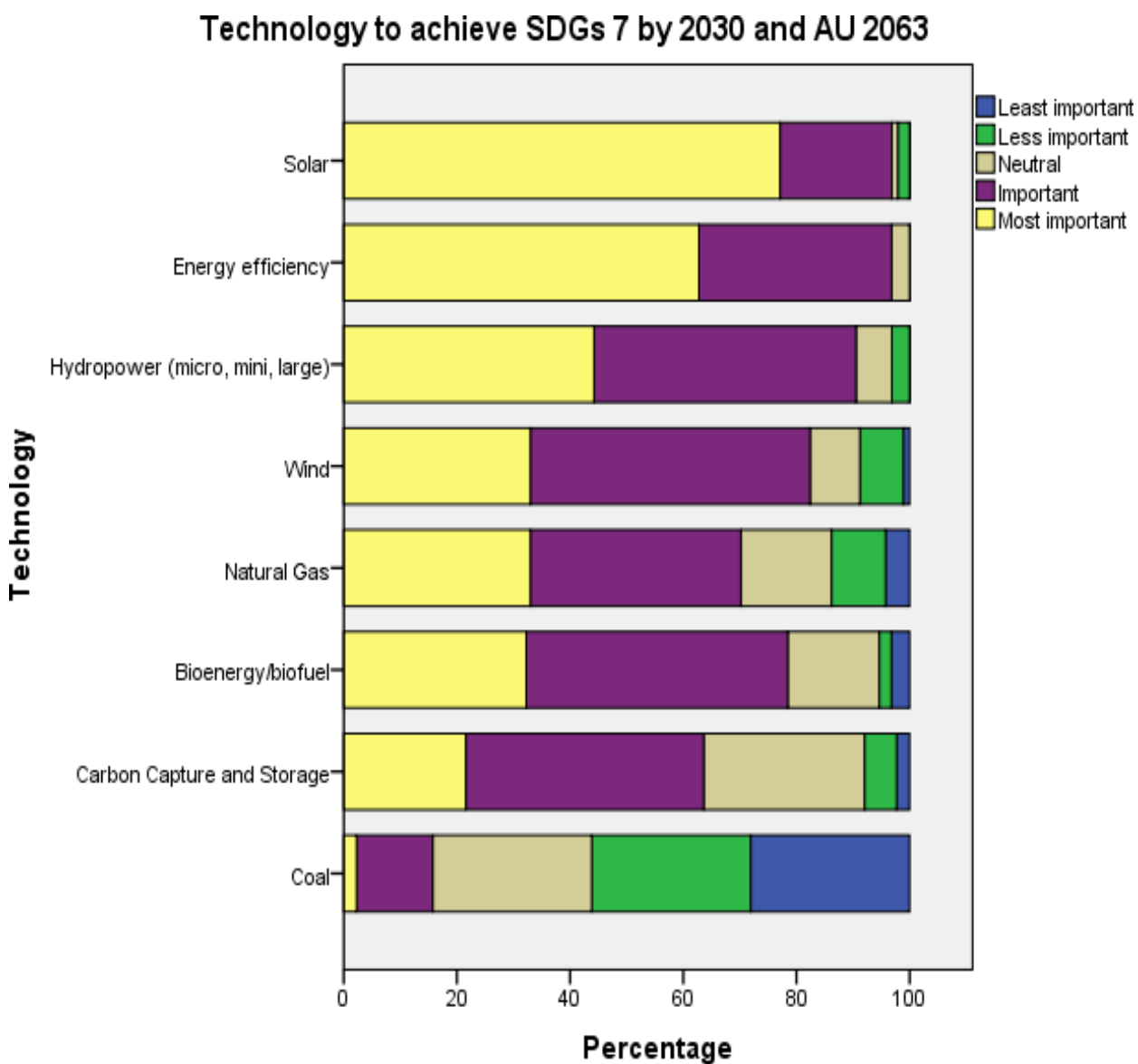


Figure 2. 7. Technology to be invested in to enhance resilience against climate change impact.

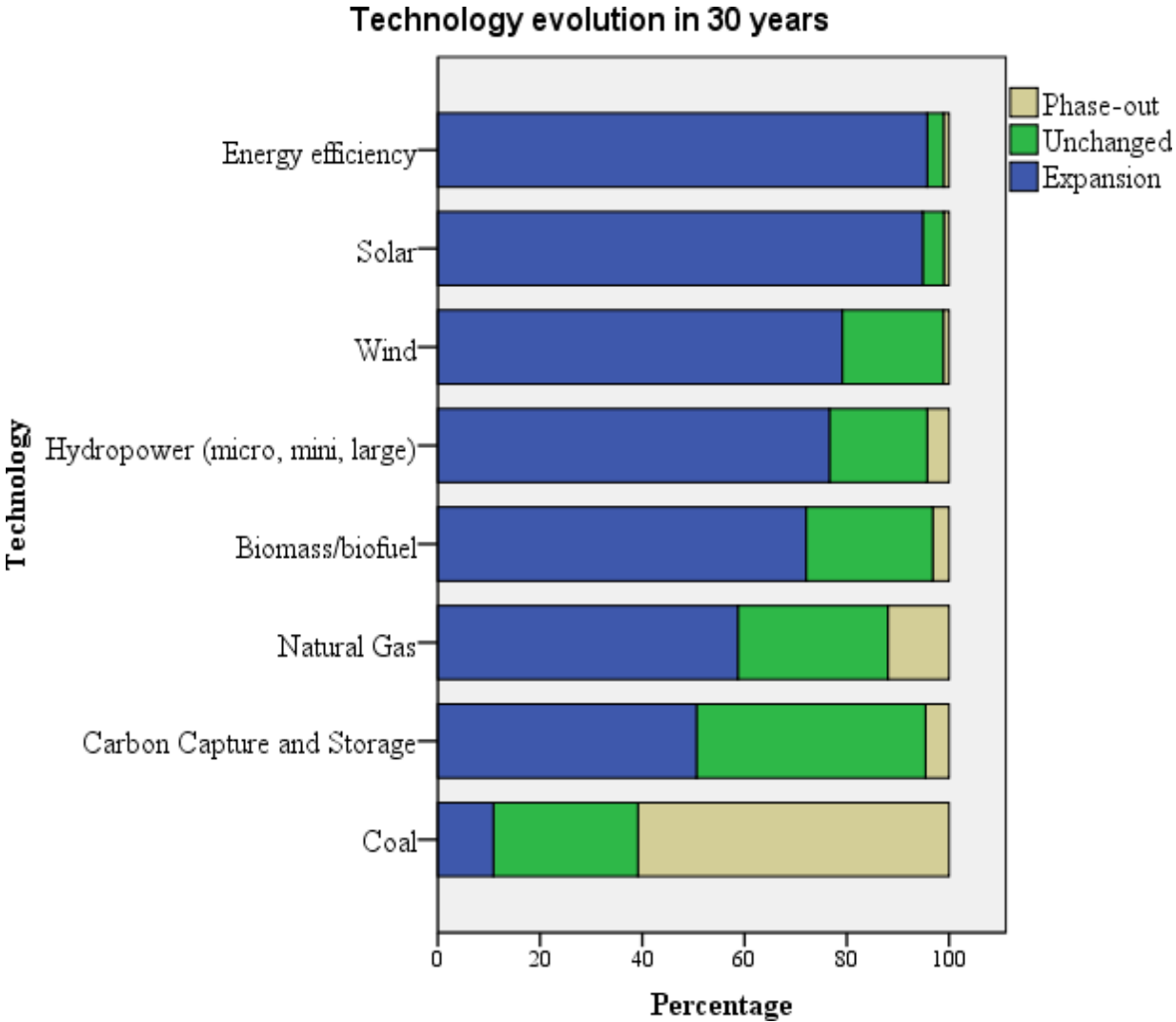


Figure 2. 8. Evolution of technology in Nigeria.

2.4.4. Financial Innovation for low-carbon Future

This subsection examines stakeholders’ views on financial innovation, which would otherwise be prioritized to achieve appropriate clean energy development in Nigeria. In Figure 2.9, stakeholders’ responses indicate that Nigeria is not giving much attention/consideration to low- carbon actions in the annual budget. However, respondents proffer solutions that would push energy transitions to the national debate to gain relevant attention in the country’s yearly budget.

Energy transition and annual budget (%)

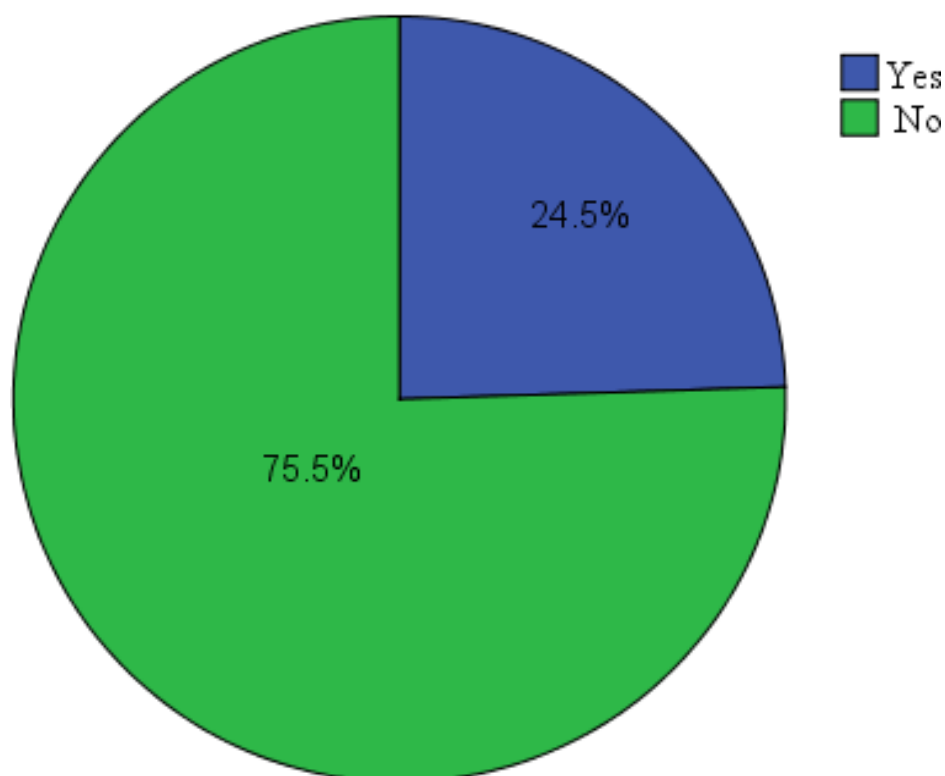


Figure 2. 9. Allocation of energy transition development in Nigeria's national annual budget. Respondents who claimed that the country was not giving much attention to energy transition in its annual energy budget suggested some innovations that could enhance transitioning to clean energy. Responses in Figure 2.10 show that clean energy advocacy (21.4%) and proper policy and implementation (27.6%) of low-carbon energy initiatives were considered innovations that could enhance energy transitions to gain relevance in the nation's budget (Figure 2.10). However, about 1.01% of respondents claimed that commitments to climate change, such as the Paris Agreement, could drive this innovation. This commitment implies that policy and implementation, advocacy, investment through subsidy and partnership (with relevant local and international stakeholders), and capacity building are relevant innovations that would significantly promote investment in Nigeria's clean energy space. The respondents further revealed that driving all financial innovations to motivate clean development was essential to achieving a low-carbon future. About 54.1% of the stakeholders identified tax holidays on renewable energy components such as batteries, solar panels, connecting cables, etc., as the most important among other financial

instruments shown in Figure 2.11. About 51.5% of stakeholders also argued that low-interest rate loan by commercial banks to investors of clean energy projects was also a relevant financial tool.

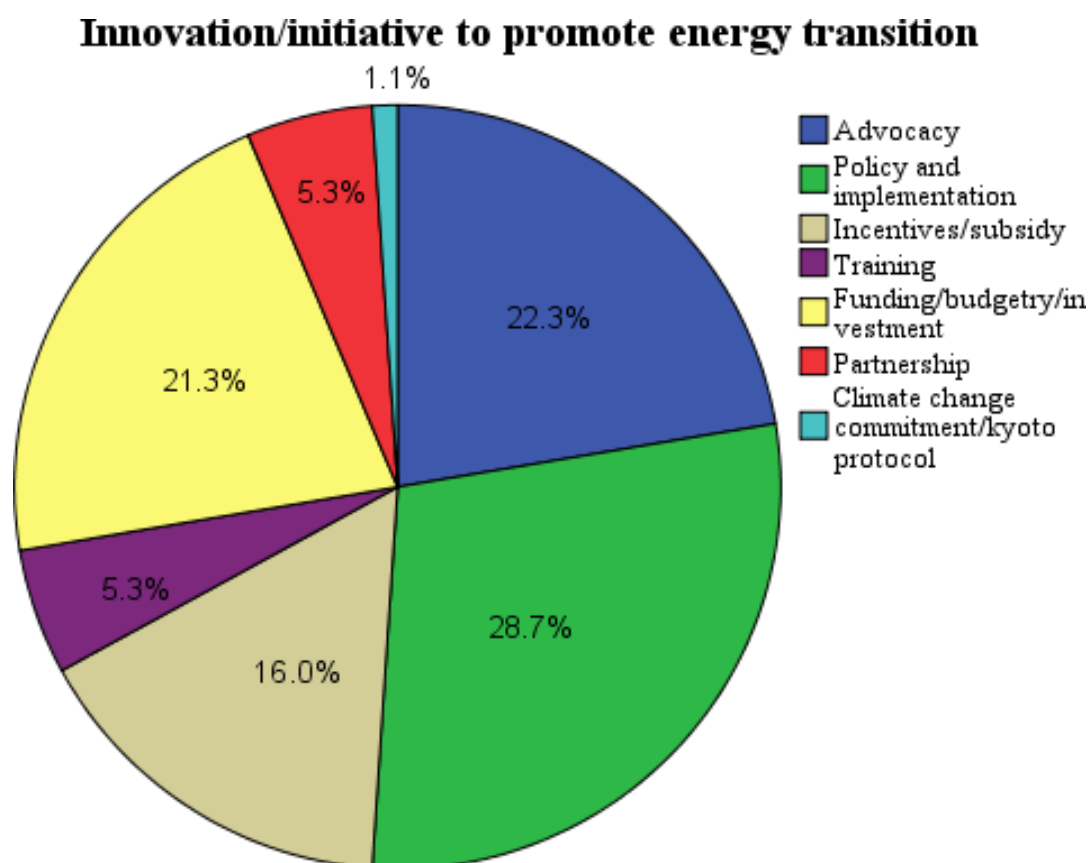


Figure 2.1 10. Innovation for low-carbon Energy to Support energy transition in Nigeria.

Access to foreign exchange (FOREX) is also found to be a financial instrument that could facilitate the importation of RE components. No respondent perceived this innovation as less or least important, as shown in Figure 2.11; easy access to grants for investors is also considered an instrument to drive renewable energy penetration. Further, the outcomes in Figure 2.11 revealed that all financial tools or innovations were relevant but should be aligned with the necessary renewable energy intervention to augment the nation's clean energy ambition for the near and far future.

Financial innovation to achieve low-carbon energy

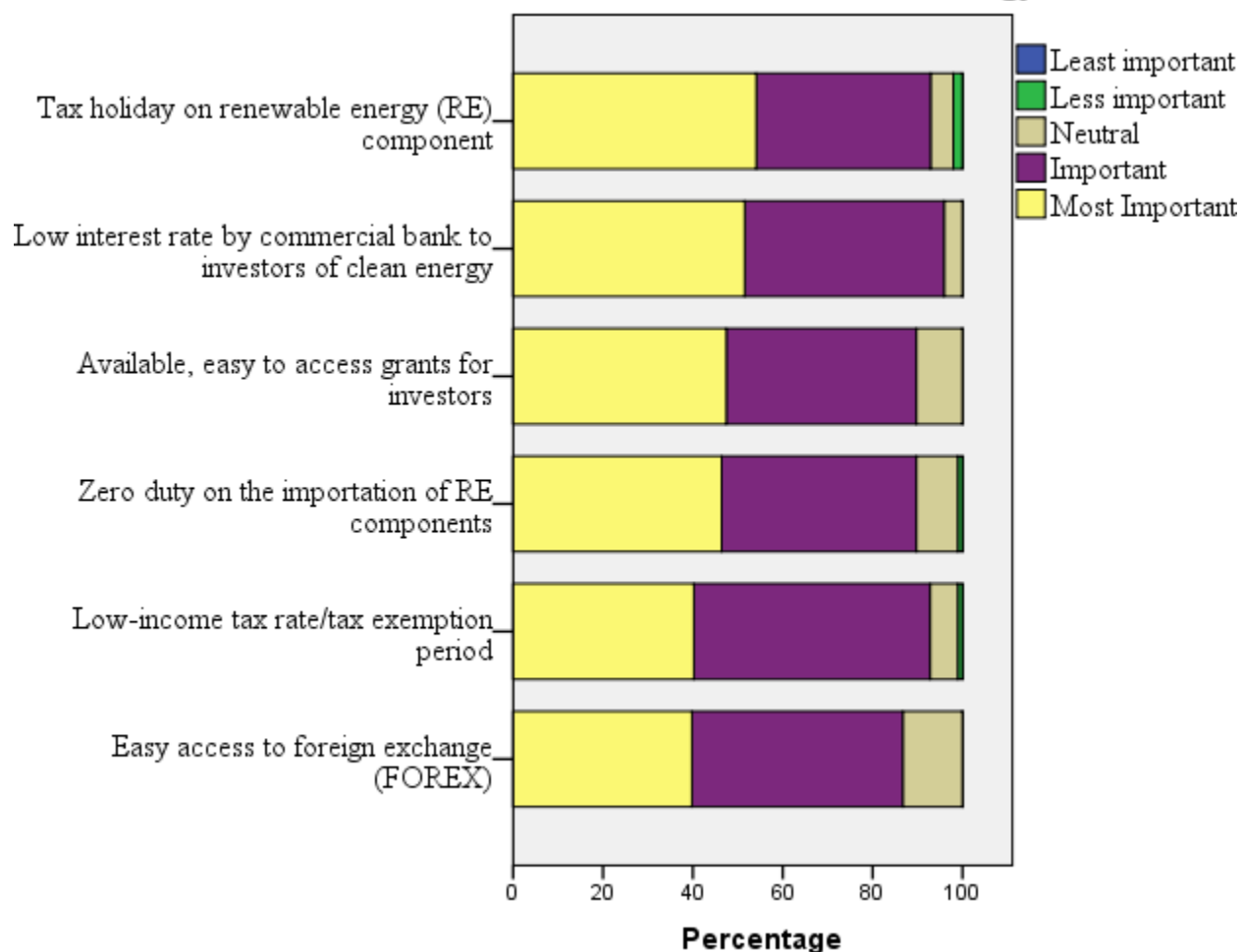


Figure 2. 11. Financial innovations to enhance a low-carbon energy transition.

This study also accessed stakeholders' views on random issues ranging from price, research and development, liberalization, partnership, energy efficiency and behaviour, tariffs, and social aspects of the energy transition. Figure 2.12 depicts these viewpoints. It can be observed from Figure 2.12 that investing in research and development, mainly in clean energy projects (59.4%), and incentives that encourage energy efficiency behaviour (57.9%) could expand the number of clean energy users. Prioritizing these types of investments would undoubtedly foster the achievement of the needed low-carbon transition goals. Most of the respondents were neutral to the conclusion that an increase in electricity tariff from the grid would encourage low-carbon development. However, about 41.7% of respondents agreed that an increase in the price of fossil-fuel products (e.g., petrol, diesel) could promote low-carbon development and the much-needed energy transitions in the power sector. Meanwhile, a few respondents, 31.6% and 15.8%,

"disagreed" and 'strongly disagreed," respectively, that full engagement of private investors could slow down the energy transition process. This behaviour implies that the involvement of the private sector would be beneficial in enhancing future clean energy development in Nigeria.

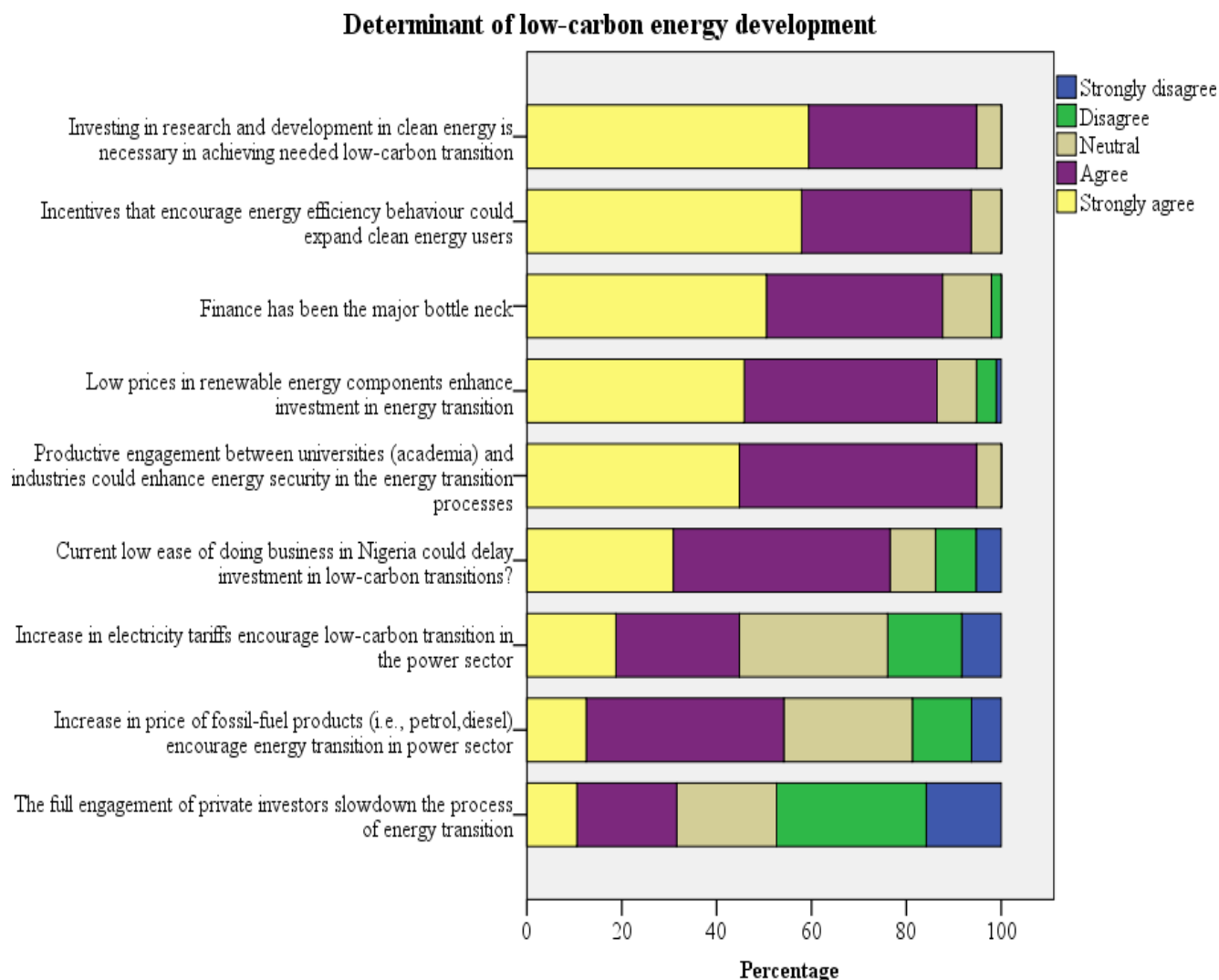


Figure 2. 12. Selected drivers of a low-carbon energy future.

In addition, respondents claimed that the current ease of doing business in Nigeria had delayed investment in clean energy. This Assertion could be due to issues related to insecurity in some parts of the country, the COVID-19 pandemic, and the current recovery from the economic recession. In conclusion, financial innovations such as incentives, subsidies, tax holidays, interest rates, FOREX, and access to grants are innovations considered alongside:

- i. investments in research and development,

- ii. prices of energy efficiency appliances, and
- iii. partnerships with relevant academic and research institutes.

The three points above may help facilitate the transition to clean energy. Therefore, it is worth noting that efforts geared towards achieving a clean energy future in Nigeria were interlocking and thus followed a causal relationship pattern.

2.4.5. Inferential analysis on energy transition

We conducted the inferential analysis of the study considering energy transition as the dependent variable and variables such as finance, motivation, technology, information and innovation were independent variables. This implies that the inferential statistics have assessed the correlation between energy transitions and the listed independent variables. While considering the hypothesis the following results were obtained and stated in sub-section 4.5.1

A. Energy transition and technology

Person product correlation of energy transition and technology was found to be weak positive and statistically significant ($r = 0.377$, $p < 0.001$). Hence, H_a was supported. In other words, this shows that advancement in technology will encourage the use of modern energy sources like natural gas and solar as against the use of traditional and unclean energy sources such as charcoal and firewood which are not environmentally health-wise unfriendly. In addition, a p-value of 0.000 ($p < 0.001$) implied that we reject the null hypothesis and accept the alternative hypothesis that indeed, technology has a significant effect on energy transitions at a one percent level of significance. This further reiterates that technology is a key factor to consider in facilitating the transition from the use of unclean energy to cleaner energy sources.

B. Energy transition and motivation

The result revealed that the correlation coefficient of 0.321 implies that the association between energy transition and motivation is positive but weak. This further implies that if stakeholders are better motivated, they would be willing to embrace clean energy and thus transition to a clean energy future. Also, a p-value of 0.001 implied that we reject the null hypothesis and accept the alternative hypothesis. This further implied that motivation has a significant effect on energy transitions. Thus, we accept the alternative hypothesis.

C. Energy transition and finance

Person Correlation analysis of finance as an independent variable and energy transition as a dependent variable revealed a correlation coefficient of 0.466, this implies that the association between energy transition and finance is positive, with a moderate relationship. It implied that finance played a significant role in achieving energy transition. Moreover, a p-value of 0.000 implied that we reject the null hypothesis and accept the alternative hypothesis that indeed, finance has a significant effect on energy transitions at a one percent level of significance. This further reiterates that finance is a key factor to consider in accelerating the transition from the use of unclean energy to cleaner energy sources.

D. Energy transition and information

Correlation analysis between energy transition and information showed a correlation coefficient of 0.130, this implies that the association between information and energy transition is positive but very weak. Also, the same analysis revealed a p-value of 0.202, the p-value is way higher than the level of significance (to be precise at 0.01). This implies that we accept the null hypothesis and reject the alternative hypothesis. Further, it implied that there is not enough evidence that a correlation exists between information about energy transition and the transition itself.

2.4.6. Qualitative analysis of the survey

This subsection shows the themes and subsequently explains the outcome of the interviews of some selected stakeholders affiliated with the NPS. The authors identified four basic themes resulting from the analysis of the qualitative data, they include, i) technology; ii) incentives; iii) advocacy; and iv) clean energy behaviour. These four themes are in tandem with results obtained from the quantitative analysis. Interviewed stakeholders were willing to share their experiences and perspectives about the future of the Nigerian energy sector, especially in the power sector. Some unusual trends were observed in the qualitative outcomes which would require a causal approach to further simplify its complexities.

On this note, a causal loop diagram (CLD) and a word cloud modelling approach were employed as qualitative modelling approaches to explore in detail the four key themes identified from the analysis of the quantitative data. Patterns were generated to enhance proper visualization of the outcomes and how one variable could have a qualitative impact on the other. More so, the

wordcloud thus shows consistency and frequency in the survey result. Figures 2.13 and 2.14 show the most frequent words used by respondents to describe their opinions about energy transitions. These views are illustrated in the wordcloud and the causal loop diagram in Figures 2.13 and 2.14, respectively. Figure 2.13, which represents the wordcloud relative size, elucidates the most frequent words used by respondents and most relevant to Nigeria's energy transitions. Most respondents felt advocacy was the most pertinent instrument that could enhance future clean energy in Nigeria. However, renewable energy was mainly considered to be a paramount factor (especially solar photovoltaic). In contrast, energy efficiency and behaviour, Feed-in Tariffs (FiT), and technology transfer, in that order, were also considered as necessary as clean energy drivers. Furthermore, respondents considered rebates, tax exemptions, and loans as some essential financial measures that could enhance Nigeria's clean energy solution.

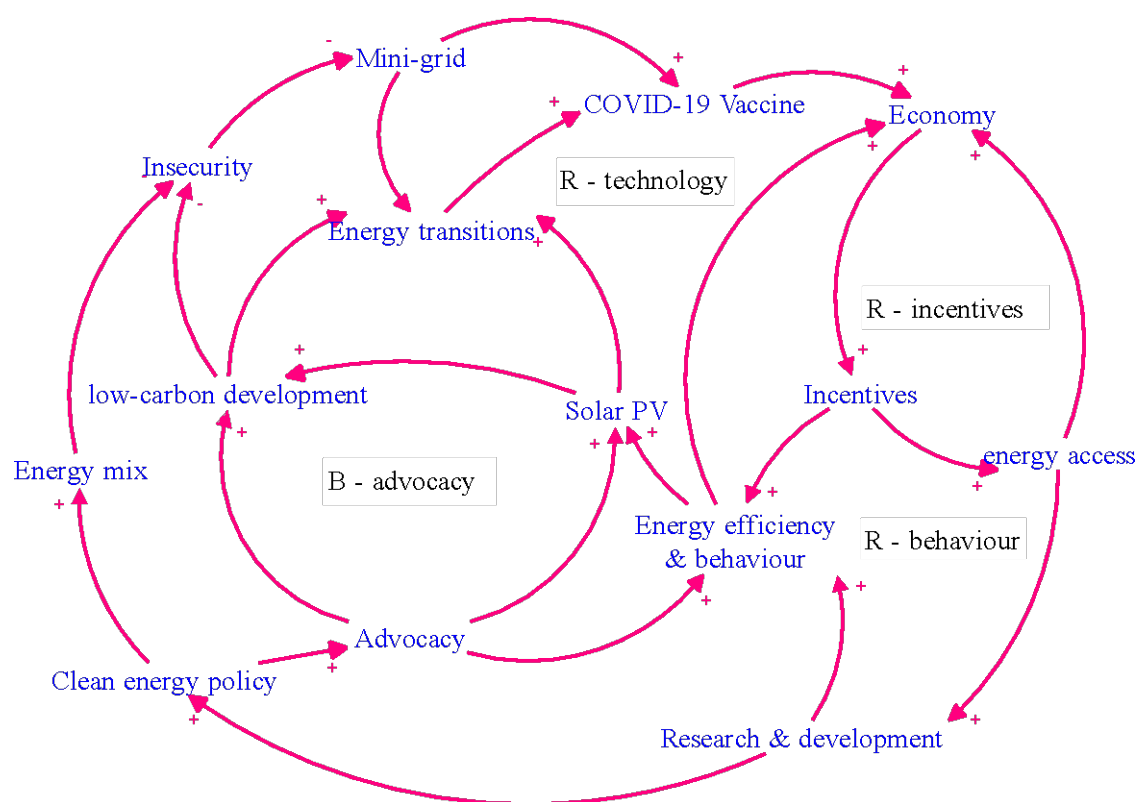


Figure 2. 14. Causal loop diagram for national energy transitions.

Outcomes from the interviews revealed that advocacy in all its ramifications is relevant; the development of renewable energy technologies and energy efficiency technologies and behaviour, among other parameters, is crucial to achieving a clean energy transition. Results from quantitative data fit perfectly and support all that we obtained from the qualitative survey.

A careful and closer assessment of the CLD would suggest that energy transition in the power sector would be driven not only by technological innovations but more by the appropriate policies. However, vices such as insecurity and the COVID-19 pandemic should be put in proper check as these could negatively impact the favourable outcome of technology innovation in the country. More so, there is a need for behavioural change among present and proposed users of modern energy, this would encourage the adoption of energy efficiency and energy conservation as an ancillary driver of clean energy transitions. Further, financial incentives if well deployed among users will have a high tendency to motivate users and more adoption of clean

technologies. The effective use of financial incentives is in resonance with the result obtained from the quantitative analysis.

Finally, the qualitative analysis of the data revealed that advocating through encouragement, promoters, and clean energy campaigns across different strata of Nigerian citizens would increase their awareness and inform them of the need to utilize clean technologies, and, thus, support the clean transition paradigm. Quantitative analysis revealed that advocacy in the form of information had no significant effect on the energy transition. Authors contend that information might not have a direct effect on the energy transition. However, it would have to be specific, as in the qualitative study. In that study, advocacy was revealed to be a primary driver of the energy transition, but other factors have also been identified and attributed to advocacy.

2.5. Discussions

Developing a national low-carbon energy future requires a concerted effort of relevant affiliations in the energy sector. This study assessed the views, perspectives, and interests of relevant stakeholders in the Nigerian power sector towards developing a clean energy future. This section discusses outcomes from the results analyzed by explaining insights gained from stakeholders' opinions and views concerning low-carbon energy development in Nigeria. Despite the NPS undergoing several structural changes towards a low-carbon energy future, and with the nation's low inclusion of renewable energy in its energy mix, the current study discusses issues concerning approaches through which the country could achieve pathways to a robust clean energy future.

The study argues that there exists a strong relationship between advocacy and academic curriculum for promoting low-carbon development. Energy efficiency and solar energy (importantly, energy efficiency standards and solar photovoltaic) would be the most significant technologies, with a greater expansion in the future compared to other clean energy technologies. It was also deduced from Oyedepo (Oyedepo, 2012) that to achieve a sustainable clean energy future, the full exploitation, and promotion of renewable energy resources, and energy efficiency practices across all sectors would be required. This observation is in agreement with the findings in this current study. This work found that attention and investment should be directed to developing capacity in solar photovoltaic and related technologies. This outcome is in tandem with Sorman et al. (Sorman et al., 2020) on stakeholder's preference for energy transitions that primary solar PV, among other

clean energy technologies, would be the most preferred energy technology in the near future.

Necessary structural changes to the Nigerian infrastructure system to enhance solar energy penetration and energy efficiency standards are critical to the sought energy transitions. This suggests that training in electricity management and supply from renewable energy (such as in solar photovoltaic) should be included in the ongoing Tertiary Institutions Entrepreneurship Scheme (TIES) by the Central Bank of Nigeria (CBN, 2021). We also found that nuclear energy is likely to gain prominence in the far future. The utilization of fossil-fuel sources, viz., natural gas, is the most preferred energy source in transitioning to cleaner energy. Accordingly, this could form a significant portion of Nigeria's future energy low-carbon mix and unlock some economic opportunities for the country if properly harnessed.

The study also maintains that advocacy in the form of public information about energy-efficient products, such as energy-saving bulbs and caution on phantom load (removal of electric devices from power sources when not in use) in residential, commercial, and industrial sectors, should be prioritized. Lindberg & Kammermann (Lindberg & Kammermann, 2021) observed over Europe that advocacy could accelerate the European energy transition. Also, the United Nations identifies advocacy and policy for clean energy as an effective energy transition strategy towards achieving SDGs 7 (UN, 2021). The UN report affirms that policy framing is an effective action plan for clean energy. This institution also asserts that a holistic assessment must inform energy system planning, economic policymaking, and other policies; this step is necessary to ensure a just and inclusive energy transition at the regional, national, and local levels” (UN, 2021).

In contrast, this work, in line with Ugwuishiwu *et al.* (2019) affirms that coal utilization alongside CCS might not happen soon due to low technical know-how, and a resultant exponential increase in the price of electricity. According to the current technology status and future outlook of the CCS in developing countries, CCS development in emerging economies is uncertain. This development may not be adopted due to the novelty of the technology in the region (Kulichenko & Ereira, 2011). Future energy should also be driven by an energy policy that makes clean energy affordable, reliable, and sustainable.

Furthermore, the study found that to enhance clean energy, the government should expand low-carbon technologies and efficient behaviour through prioritized financial innovations. These

financial tools may include tax holidays on renewable energy components, low-interest rates, easy access to finance, and incentives that will encourage energy efficiency behaviour. A similar study by Sorman et al. (Sorman et al., 2020) affirmed that revenue from environmental taxes is preferred among stakeholders to finance energy efficiency and renewable energy. Careful consideration of these tools would mean that the major bottleneck, i.e., finance needed to achieve a low-carbon energy future, has been removed. Further liberalization of the power sector could also drive the required low-carbon future.

More so, the current study revealed that variables such as technology, motivation and finance are significant to achieving energy transition in the Nigerian power sector. Our result is in tandem with Shari et al (Shari *et al.*, 2022). The study argues that finance and motivation are the main drivers of energy transition in Nigeria, likewise, Hall *et al.* (2018); IEA (2021a); Temmes *et al.* (2021) and Isah *et al.* (2023) identified finance as a significant driver of achieving low carbon development, also, the study argues that finance towards energy transition should look beyond affordability. More so, Armi et al. (2020); Temmes *et al.* (2021) and Isah *et al.* (2023) buttress the role of finance in energy transition revealing that small sizes of investments could increase the transaction cost of projects and financing. However, the result from the current study revealed that information might not play a significant role in the transitioning processes to clean energy in Nigeria. However, the role of information does not have a direct effect on energy transition in developing nations due to weak infrastructure that could facilitate effective information capturing and dissemination among clean energy users. This implies that there could be insufficient information that enhances the development of low-carbon utilization in developing countries, especially to facilitate energy access (WHO, 2009).

2.5.1. Policy Implication on the Evidence of low-carbon Energy Future

- i. The nation should give active verbal support through advocacy on developing low-carbon energy across the four sectors: i) residential, ii) commercial, iii) transportation, and iv) industrial.
- ii. The nation should develop a sustainable clean energy policy and subsequently pass into law the clean energy agenda.
- iii. The nation should ensure the inclusion of energy transition studies into the curricula of educational institutions.
- iv. The nation should ensure that future clean energy will be affordable through subsidies and rebates, thus enhancing sustainability.

2.5.2. Policy Implication on technology preferences

- i. The nation should prioritize solar energy and speed up investment in renewable, i.e., solar photovoltaic and thermal, among other clean energy technologies, to fast-track achieving SDG 7.
- ii. The nation should intensify its efforts towards the promotion of energy-efficient technologies and conservation.
- iii. The nation should enhance natural gas development (among other fossil fuel sources) for power generation, while nuclear should be considered a future driver of clean energy.
- iv. The nation should enforce measures that enhance decentralization and smart energy systems.

2.5.3. Policy Implication on financial innovations

- i. The nation should consider tax holidays as a financial innovation on RE components, such as solar panels, batteries, the balance of the system (BOS), etc.,
- ii. The nation should enhance investment in research and development in clean energy.
- iii. The nation should encourage energy efficiency by incentivizing energy management with the appropriate financial tools, e.g., low-income tax rates/tax exemption period on energy-efficient components.

Finally, based on the results, we recommend that assessing stakeholder perspectives and preferences on energy transition is germane to planning a low-carbon future. In addition, the

study presents a sustainable approach to identifying critical drivers for relevant legislation to achieve policy insights that will compel a low-carbon development.

It was noticed that the current analysis had some caveats.

First, stakeholders' perception of the Nigerian energy transition agenda was assessed as ways the proposed transition framework could be achieved. While stakeholders' opinions and perceptions are important to achieving energy transition, it is worthwhile to mention that they could misestimate the transition process and the complexities involved. Consequently, future studies could assess its complex dynamics, which would examine how current energy challenges in Nigeria could influence the temporal scale of energy transitions. More so, the current study only considered stakeholder perspectives on transitioning to clean energy with a focus on the power sector. Though the power sector needs significant reform and transition to modern electricity, other sectors need to be investigated such as transportation, clean cooking, and refineries.

Second, we explored stakeholders' perspectives concerning four thematic trends, i.e., (i) energy transition and its motivation, (ii) information/knowledge about energy transitions; (iii) technology that could shape this transition; and iv) perception due to finance. In reality, other thematic factors (e.g., market dynamics, socioeconomic, and techno-economic factors) can influence energy transition beyond the thematic areas considered here. This implies that there is room for further analysis of the Nigerian energy transition considering these thematic areas.

Third, due to the nature of the analysis (i.e., descriptive, inferential statistics, and casual loop analysis), outcomes should be considered as perception, opinion, and as such a qualitative analysis. Although, the analysis considered was more likely to inform Nigeria about its future, a detailed numerical analysis would provide a more precise and quantitative evaluation. While acknowledging these limitations, our analysis has shown the overall stakeholders' dynamics surrounding the Nigerian energy transition to clean energy and beyond. This is in addition to the existing evidence base for policymaking on the subject matter of our inquiry.

2.6. Partial Conclusions

The study confirmed that careful interaction between core motivation, information on low-carbon development, technology preference, and financial innovations are areas that would determine low-

carbon energy evolution in the Nigerian power sector.

This study, therefore, concludes that low-carbon development in Nigeria is feasible with the use of appropriate financing tools, technology development, and behaviour. Improved advocacy is also a significant means of building confidence in energy efficiency behaviour. This method could be driven by developing appropriate clean energy policies and collaborations with national and international partners. However, it is preferable to adopt a combination of clean technologies alongside investment in natural gas. This type of approach appreciates integrating a top-down and bottom-up way to planning a low-carbon energy future in Nigeria - a combination of supply (technologically driven) and demand-side management in national energy system planning (Ghersa, 2015).

There is a need for further liberalization of upstream and downstream of the power sector to enable the involvement of more relevant stakeholders in clean energy projects across the various stages of energy transitioning in Nigeria. Energy finance plays a crucial role in achieving a low-carbon future. However, no best financial innovation perfectly fits the energy transition, but specific innovation would be required to drive a particular technology or approach (be it bottom-up or top-down or hybrid). Hence, to reduce investors' risk on investment in renewable energy and energy efficiency projects, proper allocation of financial incentives could alleviate threats to investment in clean energy.

Additionally, further perspectives could consider developing scenario pathways to a low-carbon energy future from a stakeholder viewpoint through an analytical approach. Such an analytical approach could include optimization and modeling the evolution of low-carbon energy transition pathways, design of low-carbon energy scenarios and system flexibility, which allow analytical assessment of intermittent renewable penetration and explore appropriate energy efficiency policies.

CHAPTER THREE

LOW-CARBON ENERGY SYSTEM MODELLING FOR ENERGY TRANSITION: ASSESSMENT OF OPEN-SOURCE MODEL AND OSEMOSYS APPLICATION

3.0. Introduction

The energy sector – electricity, transportation, heating and cooking – accounts for about 73.2% of global greenhouse gas emissions (Ghosh, 2020). The energy sector contributes about 40 percent of global emissions of CO₂ (Foster & Bedrosyan, 2014). However, the electricity sector is the largest source of global fossil carbon dioxide emissions, emitting about 14.3 GtCO₂ eq in 2021. These emissions accounted for roughly 38% of global CO₂ emissions that year. This chapter focuses on the electricity system. Ensuring a reliable electricity supply at the lowest cost possible is the primary concern in electricity planning (UNDP, n.d.).

Renewable Energy Technologies (RET) are one of the pathways to decarbonizing the energy sector and reducing fossil fuel dependency. Reaching individual country renewable energy targets faces various barriers, where developed and developing countries respond differently. Developed countries use policy instruments such as feed-in tariffs (FIT) and a carbon tax to enable investment in renewable energy (Dannenber *et al.*, 2008). As against this, such cost policies cannot be easily implemented in many developing countries, because government policies have been overburdened from subsidizing fossil energy (Zyadin *et al.*, 2014), Nigeria is a good example of this.

Despite that the developing countries, especially in sub-Saharan Africa are the most minor emitters but have experienced the greatest negative impacts of global warming and climate change. Many countries in the region are signatories to the Paris Agreement which aims for an ambitious reduction of greenhouse gas emissions across all sectors. They have thus developed several emissions pathways to achieve their local and national emission reduction goals (UNFCCC, 2015). Transitioning to a low-carbon energy system is considered a global concern, to achieve a global clean energy sector focus should be placed on developing national and regional clean energy strategies (Sovacool, 2016). This means that to achieve a global decarbonized economy, all nations must be committed to reducing emissions from the energy sector. In addition, developed countries should support developing countries to attain their Nationally Determined Contributions. Support in the form of finance, technology transfer, training, and human development is crucial.

Despite developing countries in the SSA's less significant CO₂ emission rate, they are motivated to embrace the UNFCCC framework. The countries were also incentivized to ensure efforts and activities that ensure emission reduction across all sectors, including the power sector. This deliberate act will significantly benefit the region in achieving its Sustainable Development Goals (SDGs), and Nationally Determined Contributions (NDCs). Aside from achieving their international commitments, countries in the region stand a chance to improve their electricity access and reduce poverty. This is if pragmatic and decisive actions are taken to abate local and national emissions. However, in many sub-Saharan African countries, the concern is not wholly to reduce their carbon footprint, as the continent is not a significant greenhouse gas emitter. Africa contributes to only about 2–3 percent of the world's carbon dioxide emissions from energy and industrial sources (UNCCC, 2006). But rather, the region is focusing on how to sustainably harness its existing resources to meet its energy-growing demand for economic development and to lift its citizens out of poverty, while following a sustainable path to a net-zero future.

About 90 million people out of the over 200 million people living in Nigeria do not have access to modern energy to meet their energy needs. The significant gap in the number of people without electricity makes the World Bank consider the country as the World energy poverty headquarters. This and many other reasons make Nigeria an ideal sub-Saharan African country representation without access to modern electricity (Nduka, 2021). Their respective power supplies are unstable, insufficient, and unreliable. Nigeria has abundant renewable energy resources, such as wind, solar, and water. Thus, a lack of effective policies and poor management prevent development. To be specific, the country has a huge hydropower reserve of about 10,000 MW and 734 MW capacities in large and small hydropower, in that order (Ohunakin *et al.*, 2013). Wind energy, with a potential of about 150,000 Tera joules per year, solar radiation estimated at 3.5 to 7.0 kWh per square meter; and biomass at 144 million tonnes per year (Ukoima *et al.*, 2023). This implies that the presence of these huge renewable energy resources suggests a promising potential for generating renewable hydrogen in the country. Still, Nigeria is over-dependent on fossil fuel resources. This over-dependence has crippled and sabotaged its power sector. Further reasons for Nigeria's poor energy system range from pipeline vandalism to fuel and power theft. This has led to several grid collapses, power outages, and power sheds, resulting in over-dependence on diesel or petrol-fueled generators.

In addition, despite the meager supply of electricity an average of 3500 MW is used to meet the power needs of over 200 million people. A recent report revealed that Nigeria's electricity cost is the cheapest at 15 cents per kilowatt hour. It recorded the highest number of defaulters in the world (Ogundapo, 2023). This forced small, medium, and large-scale businesses to buy expensive captive generators powered by gasoline or diesel, threatening their survival. This fact, therefore, coerced several industries to be shut down, with some relocating to neighbouring countries. This made the prices of goods and essential commodities soar, worsening citizens' livelihood sources and impoverishing a large number of the population. It is, therefore, a fact from all indications that the provision of a stable and reliable electricity supply is a singular economic booster the country should leverage upon. This will improve the economy and quality of life of citizens.

This scenario calls for renewed and deliberate actions that both provide a sustainable, stable, and reliable power supply to meet population growth. In addition, it will improve her economic outlook which matches what is experienced in developed economies. According to a research question raised in a working paper “How should countries with many people living in absolute poverty combat climate change and energy transition while addressing poverty, creating jobs, and making progress on other sustainable development goals?” (Archibong & Osafo-Kwaako, 2023).

Climate change has severally impacted different countries in divers' measures and there is a need to develop localized measures that enhance synergy between climate change, economy, and other thematic areas. To strike a balance between meeting climate goals and achieving a clean, just transition that provides sustainable energies to meet electricity demand and enhance economic prosperity. There is a need for most developing countries to review their energy policy laws to embrace electricity generation diversification from more sustainable sources. Also, a coherent development plan focusing on the climate investment opportunity could enable Nigeria to improve its development indicators while pursuing its international climate commitments.

While climate change poses a risk to Nigeria's development prospects, it also provides opportunities to rethink the design and implementation of its national development programs (Archibong & Osafo-Kwaako, 2023). As a result, little progress has been made in implementing green transition policies (Net-zero transition plan), which aim to reduce poverty while also improving climate mitigation and switching away from fossil fuels at the same time.

However, recent government commitments through the 2021 Climate Change Act provide an institutional framework for mainstreaming Climate Change actions. These efforts also provide means for a system of carbon budgeting and establish large-scale reforms to facilitate a just transition that would similarly transform the lives of millions of Nigerians, given prompt and proper implementation (*Climate Change Act*, 2021). Still, a lot needs to be done about the Act's implementation. This would enable policymakers to gain insight into how Nigeria could gain insight into its transition to cleaner energy and uncover the accrued benefits. This approach, therefore, calls for an unprecedented paradigm shift in Nigerian understanding of the subject matter. It also calls for achieving a feasible and realistic energy policy and its subsequent implementation.

The study in this subsection, therefore, proposes that energy system modelling from a stakeholders' perspective could enhance achieving net-zero emissions in the power sector. The power sector has been chosen because it is the largest singular end-user fuel lacking and largely insufficiently available for the region, undermining its sustainable development prowess. Also, this is where emissions reductions could have the largest impact (locally and globally), however, this is not enough. To reach net-zero emissions, we need innovations across many sectors. Sustainable development also requires that electricity planning meets renewable energy targets, emissions control objectives, and energy security concerns, among other considerations.

Energy modeling is a standard analytical tool to establish renewable energy targets and policies. Most energy models are initially designed for developed countries. However, adopting energy models, without adequate compatibility assessment of the modeling tool for developing countries' energy systems may produce biased and misleading sustainable energy planning insights (Bhattacharyya & Timilsina, 2010).

To meet the aforementioned and overarching objective, the current chapter analyzes the opinions and perceptions of stakeholders regarding low-carbon energy transition and translates them into energy system modeling. The outcome from stakeholders' preferences is based on the research recommendations made in (Shari *et al.*, 2023), which inspires modeling assumptions and scenario analysis used to investigate Nigeria's energy transition plans, including the Net-zero Energy Transition Plan (NETP). More so, the current chapter also investigates the compatibility of selected

open-source energy modeling tools and how they could provide relevant policy insight into developing countries' low-carbon development.

The compatibility assessment of the open-source energy modelling tool became relevant because of 1) numerous modelling advantages the open-source tool has, and 2) not all models created by advanced countries are relevant to provide appropriate insights into developing countries' energy planning. This would provide insight to renewable energy planners and energy system modellers in developing countries on how to use analytical tools developed in advanced countries carefully.

3.1.A Synthesis of Open-source Energy Planning Tools

The initiative to support open-source energy models and open energy sector data has been going on for about two decades (Raymond, 2010). Aside from that, the open-source energy crusade has been very active and has achieved significant and successful results within open-source communities, including applications in developed countries as well as the open-source community itself (Niet *et al.*, 2021). In contrast, so far, few successes have been recorded in its application and utilization in policy development in most developing countries (Al Irsyad *et al.*, 2017). The query of this subsection is, therefore, based on: (i) the assessment of germane attributes of the open-source model to be considered when developing energy system planning in the DC context, (ii) the evaluation of important characteristics of developing countries that are essential when adopting open-source modelling tools, and (iii) how would its application translate into relevant insights for future sustainable green energy policies?

The need to gain relevant insight into the planning requirements for energy transitions in developing countries, and the use of energy system modelling tools to achieve this. However, most commercial tools lack ownership and transparency; as such their community of users is limited in this region, making it impossible to address national energy needs. Fortunately, open-source models seem to have some optimistic attributes despite some limitations. The United Nations Department of Economic and Social Affairs (UNDESA) and the United Nations Development Programme (UNDP) claimed that responding to national energy needs would require the following: (i) building and tailoring models to specific development contexts, (ii) strengthening government capacities to apply modelling tools to inform decision-making, (iii) communicating findings to the highest levels of government to guide policies (*UN Modelling Tools for Sustainable Development*,

2021.). This chapter, therefore, considers the energy modelling approaches outlined by UNDESA and UNDP to model electricity sector planning in Nigeria.

To investigate attributes of the selected open-source modelling tools were compared based on the guidelines prescribed by Indra Al Irsyad *et al.* (2017), aiming at selecting the most appropriate analytical tool. Due to the differences in emerging critical issues between developing countries and developed countries, it is necessary to examine its suitability for developing countries as well. For example, renewable energy traditionally plays a vital role as an energy source in rural areas of developing countries. However, this is not the case in many industrialized countries where their models have been largely deployed (Sovacool, 2013). To construct scenarios that investigate transition strategies in emerging nations, model ownership and a clear understanding of the modelling procedure are crucial. Essentially, renewable energy planners in developing countries should be cautious about selecting analytical tools developed by developed countries. This means that analytical tools should be selected based on free or inexpensive software options. It should also consider the purpose of the analysis and the issues pertinent to its region. Examples of pertinent issues include, but are not limited to, the traditional ways of using energy, which have informed the dynamic transition perspective.

3.1.1. Review of open-source tools

Although there are ample numbers of studies that have examined the relevance and application of analytical modelling tools for the investigation of clean energy transition in developed countries, fewer studies have investigated the selection criteria of analytical tools for developing countries.

Sovacool (2013) investigated the qualitative factors responsible for the success and failure of renewable energy access programs in 10 developing countries in Asia. The study concludes by offering 10 lessons for energy analysts and development practitioners. These lessons are (i) appropriate technology, (ii) income generation, (iii) financing, (iv) political leadership, (v) capacity building, (vi) programmatic flexibility, (vii) marketing and awareness, (viii) stakeholder engagement, (ix) community ownership, and (x) technical standardization. Outcomes from the study are useful, in that they provide relevant variables and factors to consider in developing countries' energy system planning. However, the study has only investigated renewable energy projects across Asia without considering what analytical tools would quantitatively provide

insights into green/renewable energy policy.

To overcome the bottleneck in the Sovacool study, (Lyden *et al.*, 2018) explored the modelling tool selection process for identifying appropriate tools for planning community-scale energy systems, including storage and demand side management. This same study further categorizes and documents tools and capabilities to inform modelling. The criteria for categorization include: (i) input data characteristics, (ii) supply technologies, (iii) design optimization, (iv) available outputs, (v) controls and DSM, (vi) storage, and (vii) practical considerations. While these criteria are useful, they are based on the developed and developing countries' context.

In a similar account, Bhattacharyya & Timilsina (2010) critically reviewed energy models used for energy demand assessment for developing countries. They investigated whether existing energy demand models are appropriate for capturing developing countries' specific features. It identified poor-rich and urban-rural divides, traditional energy resources, and differentiation between commercial and non-commercial energy commodities (informal economies) are often poorly reflected in these models, and also identified huge data deficiencies in developing countries. It concludes that there is a need for further development of models to better reflect the emerging country context and their institutionalizing modelling capacity is the key requirement for energy demand modelling to deliver richer and more reliable input to policy formulation in the region.

Al-Irsyad *et al.* (2017) conducted a review on selecting analytical tools for renewable energy analysis in developing Countries. The study adequately characterizes the energy attributes of developing countries by adding to research knowledge of other modelling approaches that could be considered to effectively model the energy systems of developing countries. On the one hand, the study identified systems thinking, life cycle thinking, and decision support analysis as additional approaches to modelling developing countries' energy systems. The attributes described above might not capture relevant policy insights for developing countries that use energy system models developed in developed countries. They include traditional energy consumption, economic and demographic transitions, high-income inequality, and the informal economy. On the other hand, the study did not emphasize open-source modelling tools for developing countries because little or nothing was done to address ownership and transparency issues.

Building on these backdrops, the current chapter will analyze selected open-source modelling tools

but also apply appropriate tools to explore modelling the energy sector of a developing country, a case study of the Nigerian power sector in the U4RIA guidelines (stands for Ubuntu, Retrievability, Reusability, Repeatability, Reconstructability, Interoperability and Auditability). Outcomes would provide relevant insight for energy policy formulation that would inform model scenarios for investigating pathways to meet Nigeria's climate goals, including net-zero emissions, and also support energy security, providing pathways to meet the electricity demand gap. Thus, an open-source modelling tool that captures pertinent characteristics of developing countries' energy sectors and provides succour to data dearth would be considered for subsequent analysis.

3.1.2. Open-source modelling tool selection criteria

To select an open-source analytical tool for energy system modelling in developing countries, criteria based on underlying attributes of the open-source tool and patterns pertinent to developing countries, based on Indra Al Irsyad et al. (2017), a recommendation is considered in the assessment. Assessment of criteria would consider whether open-source energy modelling tools meet the following two broad groups.

Group (A) - based on tool properties are: (i) they are user-friendly, (ii) there is available literature and country-based evidence, and (iii) their availability an open learning platform, i.e., free training, open doc, certification;

Group (B) - based on a tool capable of capturing the following characteristics of a typical developing country: (i) informal economic and demographic transition, (ii) high-income inequality, (iii) dynamic transition - these transitions include a shift from the traditional energy to the modern energy system, rapid urbanization, industrialization, energy market transformation from monopoly to liberal market, and an increase in energy consumption intensity, and (iv) financial ability and willingness of developing countries to implement recommended clean energy technologies, which are usually imported at high costs

To put the selection criteria into perspective, Table 3.1 describes common features of open-source energy modelling tools as they apply to the developing country's context. In Table 3.1, 11 open-source energy modelling tools were selected based on their intended application by the Author and on the literature to model the energy, economic and dynamic transition attributes of developing countries.

More specifically, the evaluation of open-sourced modelling tools was based on 6 criteria and 33 sub-criteria. The main criteria include (i) purpose of analysis, (ii) spatial resolution, (iii) temporal resolution, (iv) modelling approach/methodology, (v) capacity building, and (vi) attributes based on developing countries.

- i. Analytical purpose: this explains the analytical relevance of the selected open-source tool to the modeling thematic aspects of developing countries' energy systems. The criteria are based on the tool's ability to model economic, environmental, and technology. It can also integrate other sectors such as heat, electricity, transport, clean cooking, and gas integration. Also, this criterion will investigate how the tool supports the high integration of renewable energy.
- ii. Spatial resolution: this investigates the ability of the tool to capture the spatial granularity of the developing country's energy framework, based on regional, municipal, or household context. More so, the global dimension of the tools must be considered
- iii. Temporal resolution: this gives information about the model's ability to model time scales and time slices. The tool can be set to capture modelling details. Tools that can be flexible to capture specific seasons of the year and variations in the daytime such as day and night.
- iv. Modeling methodology: this investigates the modelling methodology and approach of the tool depending on whether it is simulation or optimization. It also investigates if it could be regarded as a bottom-up or top-down modelling tool to analyze micro-economics or technological aspects respectively. Also, delve into the tool's ability to use feedback systems based on system thinking or agent-based approaches, as well as the ability to compare different policy options by assessing their effects, performance, impacts, and trade-offs through multi-criteria analysis.
- v. Capacity building: this criterion assesses the availability of training and instruction materials for novice and experienced energy modeller. To further access this criterion, sub-criteria include the availability of open online certificate courses, online assistance/community of online users, and regional collaboration for model development and engagement. The criteria are relevant for energy modeller in developing countries because of the shortage of experienced modellers.

Developing countries attribute: this criterion aims to investigate modelling tools that consider some

features that characterize an emerging country's energy sector. some attributes of a typical developing country considered in the sub-criteria include large differences between rural and urban settlements, weak or lack of infrastructure to adequately collect and manage energy data, informal economies as most people in developing economies are not taxed., large gaps between the poor and rich, willingness of developing countries to adopt and implement recommended clean energy technologies. Also, the transition experienced in development is dynamic; these transitions include a shift from traditional energy to the modern energy system, rapid urbanization, industrialization, energy market transformation from monopoly to liberal market, and an increase of energy because transitions have occurred from biomass to electricity. In addition, considering the low level of illiteracy in developing countries, chances are high that there will be some level of inexperienced modelers and thus would need hands-on training.

Table 3. 1 Common features of open-source energy modelling tools as it applies to developing countries.

Criteria	Sub criteria	AnyM OD	Backbo ne	Balmorel	Calliop e	ETE M ¹²	Genx	MESS AGEix 13	OEMO F ¹⁴	OSeMO SYS ¹⁵	PYPSA 16	TEMO A ¹⁷
Analysis purpose	Economic impact	¹⁸	✗	✗	✗	✗	✗	✗	✗	✗	✗	
	Environmental impact	¹⁹		✗	✗	✗	✗	✗	✗	✗	✗	✗
	Technology mix	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
	System flexibility	✗			✗		✗	✗	✗	✗	✗	
	Sector coupling	✗	✗	✗		✗	✗	✗	✗	✗	✗	
Spatial coverage	Global							✗		✗	✗	
	Regional	✗	✗				✗	✗	✗	✗	✗	
	National	✗	✗	✗	✗		✗	✗	✗	✗	✗	✗
	Municipal		✗	✗		✗			✗	✗		
	Building/Household					✗				✗		
Temporal resolution	Annual		✗			✗	✗	✗	✗	✗	✗	✗
	Daily	✗	✗			✗			✗		✗	
	Hourly	✗		✗	✗	✗			✗		✗	

¹²Energy Technology Environment Model

¹³Model for Energy Supply Strategy Alternatives and their General Environmental Impact

¹⁴Open Energy Modeling Framework

¹⁵Open-Source Energy Modeling System

¹⁶Python for Power System Analysis

¹⁷Tools for Energy Model Optimization and Analysis

¹⁸<https://leonardgoeke.github.io/AnyMOD.jl/stable/>

¹⁹<https://arxiv.org/abs/2011.00895>

²⁰<https://github.com/pypsa-meets-africa/pypsa-africa-archived>

Modelling	Simulation											
Methodology												
	Optimization	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘
	Bottom-up	✘		✘	✘	✘	✘	✘	✘	✘	✘	✘
	Top-down		✘									
	hybrid									✘		
	System thinking											
	Multi-criteria analysis											
	Agent-based modeling											
Capacity building	Open learning Doc	✘	²¹	✘	✘	✘	✘	✘	✘	✘	✘	✘
	Free certification									✘		
	Open personal training									✘		
	Open online support						✘	✘	✘	✘		
	Regional collaborator			✘						✘	✘	
Dev Country attribute	Rural-urban dichotomy		²²						✘	✘		
	Available dataset									✘	✘	
	Informal economy								✘	✘		
	Income inequality								✘	✘		
	Willingness to adopt clean technology		✘						✘	✘	✘	
	Dynamic transition						✘	✘	✘	✘		
	Inexperienced									✘		

²¹https://en.wikipedia.org/wiki/Open_energy_system_models#cite_note-eerma-et-al-2022-119

²²https://en.wikipedia.org/wiki/Open_energy_system_models#cite_note-eerma-et-al-2022-119

3.1.3. Analysis of the synthesis

Based on the outcome from the analysis of the common features of open-source energy modelling tools, as applied to the energy characteristics in developing countries (see Table 3.1) the synthesis of the analysis is carried out. This sub-section briefly illustrates the rationale for selecting the appropriate open-source modelling tool for low-carbon energy planning in developing countries, especially in the sub-Saharan African context. This would enable further insight into the application of open-source tools are suitable to give a better insight into the energy sector in developing countries.

Model assessment criteria are based on the analytical ability of the model. Open-source tools, such as AnyMOD, Genx, MESSAGEix, OEMOF, OSeMOSYS, and PyPSA, achieved all sub-criteria based on the model's ability to assess the economic, environmental, and technological impact of policy on energy planning in the developing country's energy planning paradigm. On the other hand, other tools, such as Balmerol, Calliope, ETEM, backbone and ETM, and TEMOA, in that decreasing sequence, were found to model the analytical aspect of energy planning.

OSeMOSYS has the highest tool spatial coverage. It is applicable globally, regionally, nationally, and locally. It can also be applied across Africa, Asia, Europe, and America for different aspects of energy system planning, including the power sector and country case study (Barnes *et al.*, 2022; Dallmann *et al.*, 2022; Howells *et al.*, 2021; Mekonnen *et al.*, 2022; Olsson & Gardumi, 2021; Taliotis *et al.*, 2016). Also, OSeMOSYS has been applied to a village case study to estimate the cost of energy access (Fuso-Nerini *et al.*, 2015) at a household level²³. Specifically, the model has been employed to analyze ways to achieve strategic low-cost energy investment opportunities and challenges towards achieving universal access (SDG7) in about 45 African countries, including energy projection for African nations (Pappis *et al.*, 2019). These attributed applications are included in the Energy Model Base for Africa (TEMBA) project (TEMBA, n.d.).

²³Warren, Peter (23 September 2011). Incorporating behavioural complexity into the Open-Source Energy Modelling System using intangible costs and benefits. People and Buildings. London, UK.

Similarly, PyPSA developed a global open energy system optimization model and demonstrated it in a regional and national context, where a recent study examines various pathways for Africa to be net zero by 2060 (Parzen *et al.*, 2022). However, the author is not aware of its application at the municipal spatial scale, so also MESSAGEix. Conversely, OEMOF and backbone modelling frameworks have been applied at several spatial scales from national to municipal scales, but none of these models capture all spatial scales. However, the OEMOF model has been applied to the sub-Saharan region of Nigeria to investigate and design rural electrification systems based on multi-criteria methodology (Juanpera *et al.*, 2020). ETEM on the other hand, is reported to have a highly detailed spatial resolution and as such could represent the municipal energy system (ETEM, n.d.).

Based on temporal resolution ETEM, OEMOF²⁴, and PyPSA were found to have the most granular time slice in the sense that they can model at annual, daily, and hourly time steps (GitHub, 2023). ETEM can represent time slices of the four seasons using typically individual days or finer (ETEM, n.d.). Furthermore, based on the modelling approach, an optimization problem on Linear or mixed-integer programming aims to minimize electricity generation/supply cost with the use of an open-source linear and mixed-integer optimization solver (Al-Irsyad *et al.*, 2017). Indra claimed that solving an optimization problem in a bottom-up approach is the most feasible modelling approach for developing countries.

Regarding the availability of capacity building for experienced and novice modellers, all the investigated open-source modelling tools (find them in the footnote) are found to have open documentation. In addition, they have their respective modelling codes readily available in the GitHub repository^{25,26,27,28,29,30,31,32}. However, not all modelling tools have channels and handles to train energy modelling tool users to encourage other inexperienced users to gain an in-depth understanding of the application of the tool and enable in-country energy system modellers to own their country's energy modelling paradigm and its application. On the one hand, some modelling frameworks, such as PyPSA, OEMOF, and MESSAGEix, have structured programs or workshops. As a result, hackathon materials are made

available for beginners and experienced modelers could exchange modeling ideas and suggestions on the same platform. On the other hand, the OSeMOSYS modeling framework seems to have more engaging activities and platforms for energy modelers – beginners, intermediates, and

experienced modelers. There is also an Open University course where modelers can take free energy and flexibility modeling courses based on an integrated tool - OSeMOSYS and FlexTool (CCG, 2023). These courses not only do they combine theoretical lessons with practical exercises, but also teach users the theory behind energy modeling for investment planning on how to build an energy model from scratch.

Furthermore, there exists a comprehensive Energy Modeling Platform (EMP) that entails capacity-building programs in energy system models, where participants are across Africa³³ Latin America and the Caribbean.³⁴ Trainers are not only trained for free in energy system modeling tools but also obtain a certificate when they complete all the teaching activities. Currently, trainees are now becoming trainers across continental and national scales³⁵. These efforts have indeed fostered regional collaboration by bringing together demand-led research, data modeling, academic expertise, and training to support countries in the global south in attracting investment for sustainable development. Additionally, the free capacity-building efforts have enabled participants to gain insight through the lens of modeling to gain relevant comprehension into their country's energy transition framework, climate goals –NDCs –, and net- zero emission strategies.

The characteristics of a developing country are relevant to the choice of modeling tool methodology. This is important because the energy sector of the developing countries has characteristics of significant rural-urban dichotomy, non-availability of the relevant dataset, largely informal economy/unaccounted tax regime and income inequality, weak ability and willingness to pay and adopt clean technology, continuous dynamic transition, and inexperienced users due to the level of illiteracy. Based on this backdrop, OSeMOSYS, OEMOF, and PyPSA are identified as excellent to most effective, respectively.

²⁴<https://github.com/pypsa-meets-africa/pypsa-africa-archived>

²⁵<https://docs.juliahub.com/AnyMOD/Dh0iA/0.1.6/>

²⁶<http://www.balmorel.com/index.php/balmorel-documentation>

²⁷<https://devdocs.io/backbone/>

²⁸<https://calliope.readthedocs.io/en/stable/>

²⁹<https://osemosys.readthedocs.io/en/latest/>

³⁰<https://aglavic.github.io/genx/doc/>

³¹<https://pypsa.readthedocs.io/en/latest/>

³²<https://docs.messageix.org/en/stable/>

³³<https://climatecompatiblegrowth.com/emp-a/#:~:text=2023,accessing%20its%20large%20resource%20base>

³⁴<https://climatecompatiblegrowth.com/energy-modelling-platform-latin-america-and-the-caribbean-emp-lac/>

³⁵<https://mailchi.mp/climatecompatiblegrowth/week-121?e=d0cfd0f3e9>

A few models have been improved upon to address limitations found in other open-source modelling tools under investigation in the current study for instance, OSeMOSYS captures thematic issues of concern in developing countries. This fact can be attributed to some improvements in the model's use. First, the introduction of a user-friendly Graphical User Interface (GUI) - the ClicSAND software based on Excel (Cannone, Allington, De Wet *et al.*, 2022). These qualities make modeling in OSeMOSYS easy as the user does not interact with the command line during the modeling process. It is easy and fast to install, compatible with the Starter Data Kit models, and compatible with both Windows and macOS operating machines. Second, the availability of a Country-based Starter Data Kit (CSDK), an Excel SAND Interface to input data, and access the database to import results, and also, the ease of model simulation via an OSeMOSYS Cloud platform. In this, a recent improvement on OSeMOSYS via ClicSAND and CSDK has enabled it to overcome some bottlenecks in the use of Open-source modelling tools in developing countries. Thus, this improvement will enable better rural-urban modelling, ease of data input infrastructure and availability, enable understanding of local economy and income dynamics and processes of clean technology adoption across different transition scenarios, and support for inexperienced users.

3.1.4. Suitability Analysis

Further analysis was conducted on the suitability assessment of open-source modeling tools to model the energy characteristics of developing countries. Figure 3.1 illustrates a proportional analysis to put into perspective the tools based on a proportion of criteria assessment conducted in Figure 3.1. According to HareK (2003), a proportional analysis is a systematic approach to comparative analysis, and any scientific comparison is a verifiable reconstruction of visual information with sufficient measurable detail in a sequential alignment.

Equation 3.1. represents the proportional formula that is employed to create comparative evidence among models and their corresponding criteria and suitability for adoption in developing countries.

$$A: B = C: D \quad 3.1$$

Where A and B are extreme teams, while C and D are mean teams.

The outcome (shown in Table 3.1) of the attributes of open-source energy modelling tools was aggregated according to their common features that model energy planning in developing countries was subjected to proportion analysis, the outcome is presented in Figure 3.1. A weighting method according to equation 3.1 was employed and the outcome revealed that energy models behaved differently and showed that the assessment could provide some reliable insights into the capabilities and functions of open energy system models

Also, Figure 3.1 shows more evidence for the suitability of open-source modelling tools to model the energy system considering criteria based on modelling tools and emerging countries' attributes. Figure 3.1 revealed that OSeMOSYS, OEMOF, and PyPSA are the most preferred energy modelling frameworks to gain reliable insight into planning a low-carbon energy future in developing countries (DC).

Furthermore, OSeMOSYS' modelling tool is the most preferred among other open-source tools assessed. This status is largely due to the following capabilities of the OSeMOSYS tool: i) a significant and wide range of spatial resolution up to the household level; ii) availability of a wide range of capacity-building opportunities that will not only encourage novice modeller but also provide them with experienced modellers as mentors; and iii) unprecedented attributes in DC, such as economy, population diversity and settlements, and level of technological advances. OSeMOSYS provides modelling support in this regard.

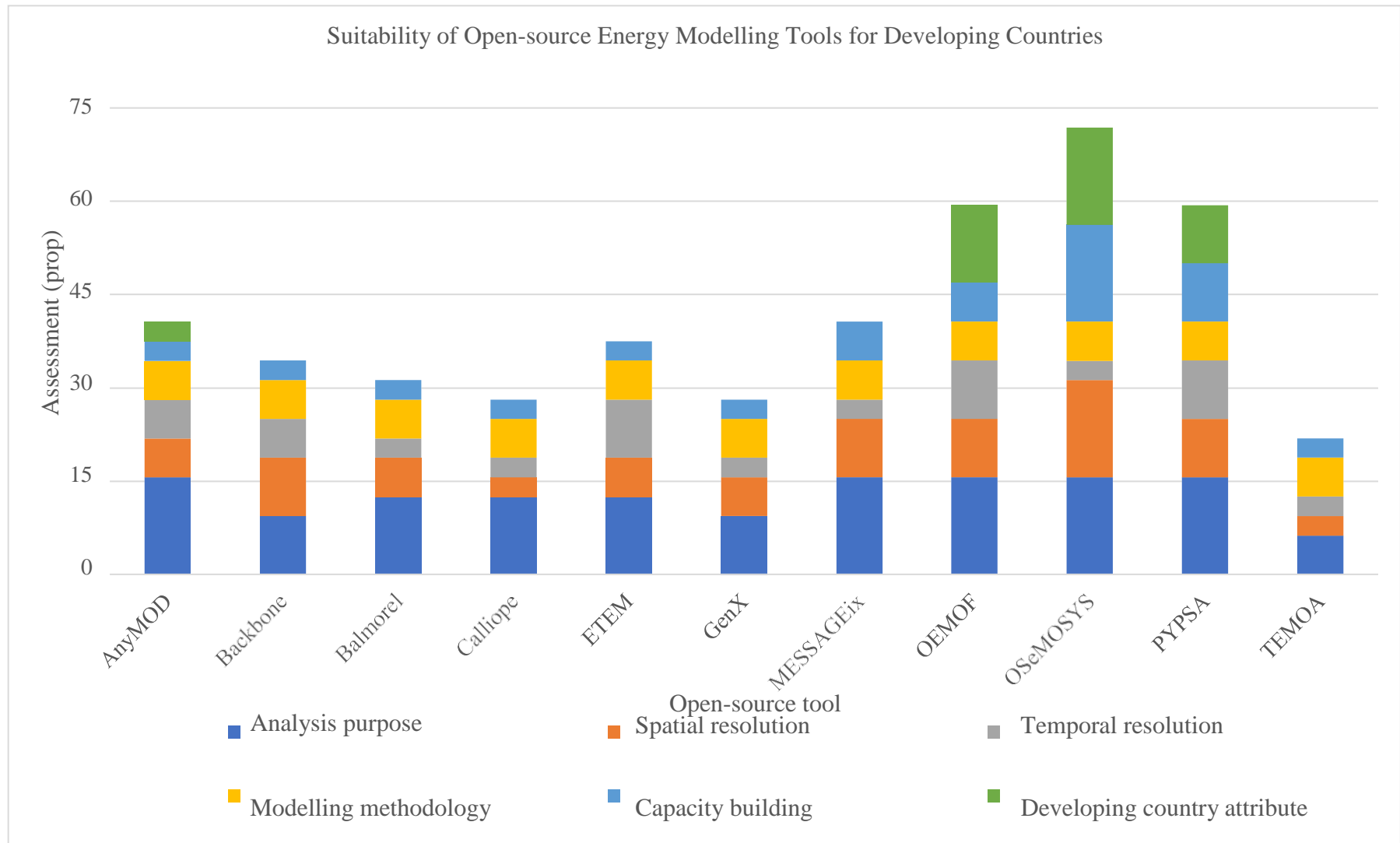


Figure 3. 1. Suitability analysis of open-source energy modelling tools for Developing Countries.

OSeMOSYS model has shown relevancy and a high level of suitability among open-source energy modelling tools for developing countries context. However, OSeMOSYS may not fare well in aspects relating to temporal resolution, as the model might not be capable of modelling highly detailed time slices in hours or days.

3.1.5. Summary of Review

Evidence has shown that there is a need to employ energy system models to gain insight into planning the transition to a clean energy paradigm in developing economies. This deliberate transition will not only improve energy access but also enable countries to achieve their climate goals. The choice of an energy model is important to consider as well as nature characteristics across the region.

Open-source energy modelling tools have been gaining international attention lately as compared to their commercial counterparts. Open-source models enable countries to take ownership of their energy future and enhance soft technology transfer from advanced countries. However, most open-source models are designed to model developed countries. If adequate caution is not taken when applied to an emerging country's context, such a modelling framework might not mainstream the appropriate clean energy policy capable of supporting sustainable implementation. Thus, there is a need to conduct a suitability assessment that compares several criteria and attributes of developing countries. It proposes a modelling tool that leverages several attributes found in a typical emerging economy.

Against this backdrop, a comparative and suitability assessment has been conducted on 11 open-source energy modelling tools by considering criteria ranging from tool properties, and analytical strength to the developing country's characteristics. Three open-source modelling frameworks were found to be most suitable for developing countries' energy contexts. OSeMOSYS is preferred, however.

3.2. A Case Study of the Nigerian Power Sector

3.2.1. Background

Energy is crucial to a country's economy as it facilitates industrial development and technological innovation (Elum *et al.*, 2017). While the importance of energy cannot be overemphasized or overlooked (Ehigiamusoe, 2020), environmental degradation associated with energy consumption constitutes a major concern as it can accelerate global climate change (Rehman *et al.*, 2021). In Nigeria, carbon dioxide (CO₂) emissions are a major environmental issue, which threatens both human lives and the ecosystem's development. Energy consumption in the country is largely sourced from fossil fuels. As a developing country seeking to sustain economic growth, there is bound to be a continual increase in energy consumption. This will increase CO₂ emissions in the country (Ali *et al.*, 2021; Jakada *et al.*, 2020). Several studies carried out in the country have produced results that support this theory and indicate that CO₂ emissions are on the rise.

For instance, Emodi & Boo (2015) analyzed CO₂ emissions from electricity generation in Nigeria. They obtained results that indicate that economic activities increase CO₂ emissions in the country. Therefore, energy sources need diversification. Similarly, Nwede *et al.* (2019) observed that the rising trend of GDP per capita symmetrically and asymmetrically caused a rise in carbon emissions. Li *et al.* (2020) also observed an increase in CO₂ levels in Nigeria due to diverse factors, such as low energy efficiency, increased energy use, economic growth, and clean energy substitution. Lin *et al.*, (2015) attributed increased CO₂ emissions in the country to population growth due to its role in increasing consumption and demand. CO₂ emissions can be attributed to fossil fuel combustion for heat generation, electricity generation, and transportation (Urban *et al.*, 2016). As such, the reduction of GHG emissions and the mitigation of climate change and its effects on the environment are largely dependent on the decarbonization of the country's energy systems as advocated globally (Dodds *et al.*, 2015; Geels, 2018; Hanley *et al.*, 2018).

Decarbonization or utilization of low-carbon energy sources has gained a lot of attention among environmental experts in recent times with the need to develop strategies to guarantee a low-carbon environment and foster an improved quality of life, attaining the required importance (Shobande & Shodipe, 2019). The simultaneous transition of energy systems for agricultural, heat, electricity, and transportation systems to low-carbon systems is required for climate change mitigation (Geels

et al., 2017). Low-carbon transitions can be described as vital changes in transport, buildings, and energy systems that significantly promote energy efficiency, bringing about a reduction in demand or causing a shift from fossil fuels to renewable fuels (Geels *et al.*, 2016). This transition aims to reduce emissions of GHGs in the process of enhancing economic growth and sustainable development (Emodi *et al.*, 2016). For such a transition to be successful, crucial changes in business strategies, technology, institutions, and consumption practices are required, thus factors such as culture, society, economy, politics, and laws need to be considered (Jabbour *et al.*, 2015).

In an oil-dependent economy, such as Nigeria, where oil production and consumption are crucial to economic growth and development, the transition to a low-carbon economy is a delicate matter as economic growth may be retarded if not controlled properly (Awodumi & Adewuyi, 2020). Hence, a strategic energy plan that considers economic growth and a gradual transition to low-energy sources for a sustainable environment is essential in achieving sustainable development goals.

Nigeria as the most populous African country is invariably one of the major emitters of CO₂. It is imperative to state here that the success of the low-energy transition program of the country, in line with the Paris Agreement aims, is critical for the entire continent of Africa. This statement is based on Nigeria's leading role in the West African economies. As a demonstration of this critical role, Nigeria published and updated her National Determined Contribution (NDC) in 2021 under the Paris Agreement. Several studies have been conducted on sustainable strategies for low-carbon development in other countries (Urban *et al.*, 2016; Hanley *et al.*, 2018; Rehman *et al.* 2021). In addition, Dioha & Kumar (2020) have elaborately explored the energy system impacts of Nigeria's Nationally Determined Contributions and low-carbon transition to mid-century.

However, no study has been conducted to investigate the role of Nigeria's climate goals such as those contained in her national plan to both cut emissions and improve clean energy access. This would, therefore, include assessing a whole sum of climate goals including net-zero emissions, NDCs, and a recent study on stakeholder preferences (Shari *et al.*, 2023) by bringing together several energy policy outlooks to gain insight into national climate goals for a holistic energy planning. Also, to explore emissions' pathways for the country and the consideration of various energy scenarios particularly applicable to the country's context.

Hence this study aims to examine low-carbon strategies towards sustainable energy transition for Nigeria using a two-fold analytical approach of scenario analysis via (i) an Open Source Energy Modeling System (OSeMOSYS) platform for the development of strategic transition pathways based on Nigeria's climate goal to explore a Net-zero energy transition plan and insights from stakeholders' analysis and perspectives and flexibility assessment through the use of FlexTool to examine the flexibility of the system to account for a high share of renewable energy penetration and ii) employ the use of an Open Energy Modeling Framework (OEMOF) to explore the use of the role of green hydrogen as a future energy carrier in the Nigerian power sector towards a net zero energy transition plan.

3.2.2. Description of Data

This subsection describes the dataset and methodology employed in the current chapter. These include the data source, structure, and how it enhances energy modeling for policy support. The approach is applied to the Nigerian power sector by considering different energy planning scenarios.

3.2.2.1. Data Description

Data employed for the study are secondary data, motivated by stakeholder analysis (Shari *et al.*, 2023), which are of refined structure and compatible with the OSeMOSYS modeling platform. Secondary data was sourced from the Energy Commission of Nigeria (ECN) and the Transmission Company of Nigeria (TCN). In addition, an open dataset embedded in the Starter Data Tool Kits developed in the Climate Compatible Growth project (Cannone, Allington, Barron, *et al.*, 2022) was used. The starter Data Kits cover all countries in mainland Africa, as well as countries across Asia, Oceania, and South America to incorporate and enhance fast policy analysis (CCG, 2020).

Datasets and a base SAND model interface are published on the Zenodo research platform (Allington *et al.*, 2021), as well as the Climate Compatible Growth Starter Data Kit Map (CCG-Map-data, 2022). In this case, data developed for the Nigeria case are considered for model development and scenario analysis. Data are collected entirely from publicly available and accessible sources, websites and databases of international organizations, journal articles, and existing modelling studies (Allington, 2021). The module uses the Open-Source Energy Modelling System (OSeMOSYS), a full-fledged linear programming optimization model, and the ClickSand

spreadsheet interface to illustrate the complexities of electricity planning in a developing country context.

The Starter Kit model for Nigeria is structured so that it has a basic structure that can be adapted by in-country analysts. The model consists of the following datasets: the techno-economic parameters of supply-side technologies such as cost (capital and fixed), operational lives, efficiency data and average capacities, and techno-economic factor data for power transmission and distribution, emission factors, renewable and fossil fuel reserves, installed capacities, and final electricity demand projection. Demand data are split by sector including industries, commercial, residential, and transport, and include power, heating, transport, and cooking demands. However, datasets are represented in CSV file format compatible with the model development platform - the base SAND interface.

To authenticate data reliability, data was used to calibrate an energy system model using the cost-optimization tool - the Open-Source Energy Modeling System (OSeMOSYS) – from 2015–2050 and in creating two stylized scenarios (Fossil Future and Least Cost) for 2020-2050. More so, it is imperative to note that full data description and model projection for datasets can be accessed from Allington (2021). In addition, the data was validated from Nigeria's energy and power sector data.

3.2.3. Study Methodology

The study employed a novel methodology, with robust energy datasets to model the Nigerian energy system's transition to low-carbon development. The model was developed using the SAND interface. Thus, this subsection describes time slices, scenarios, and data adjustments to meet the criteria in the developed scenarios. The Nigeria starter kit was improved and adopted to include a study-specific scenario while taking into account the study's policy goals and constraints.

3.2.3.1. Reference Energy System (RES)

Figure 3.3 represents the Reference Energy System (RES) based on the OSeMOSYS' framework. It shows a simplified and aggregated graphical representation of the real energy system under analysis and possible development paths. A key feature of the RES is that it illustrates existing and potential new energy supply chains from primary energy sources to final energy consumption. The RES is significant because it shows the minimum representation of reality needed to answer the study's policy questions.

In addition, Figure 3.3 shows the primary energy resources of fossil fuel, nuclear, and renewable energy in terms of whether raw energy is extracted or imported, which includes oil, natural gas, coal, uranium, water, wind, and solar. The second energy level is where raw energy commodities are refined. In the current study, all primary energy resources are transformed into electricity. These refined commodities are transmitted and distributed to the demand side to be used for useful services by the final consumer. In the commercial, industrial, and residential sectors, consumers use these refined commodities for energy services.

Finally, some energy resources transformed into useful electricity may not necessarily be transmitted through the utility grid and distributed. Such energy resources are meant for a decentralized system, whereby, the electricity generated is transmitted directly to the final consumers without being transmitted via the utility grid system. This design is common in areas with no access to the grid. As such, they have to generate their electricity from a standalone - decentralized solar PV, diesel generator set or small hydropower plants, or a hybrid system including a diesel generator. Figure 3.3 shows the design.

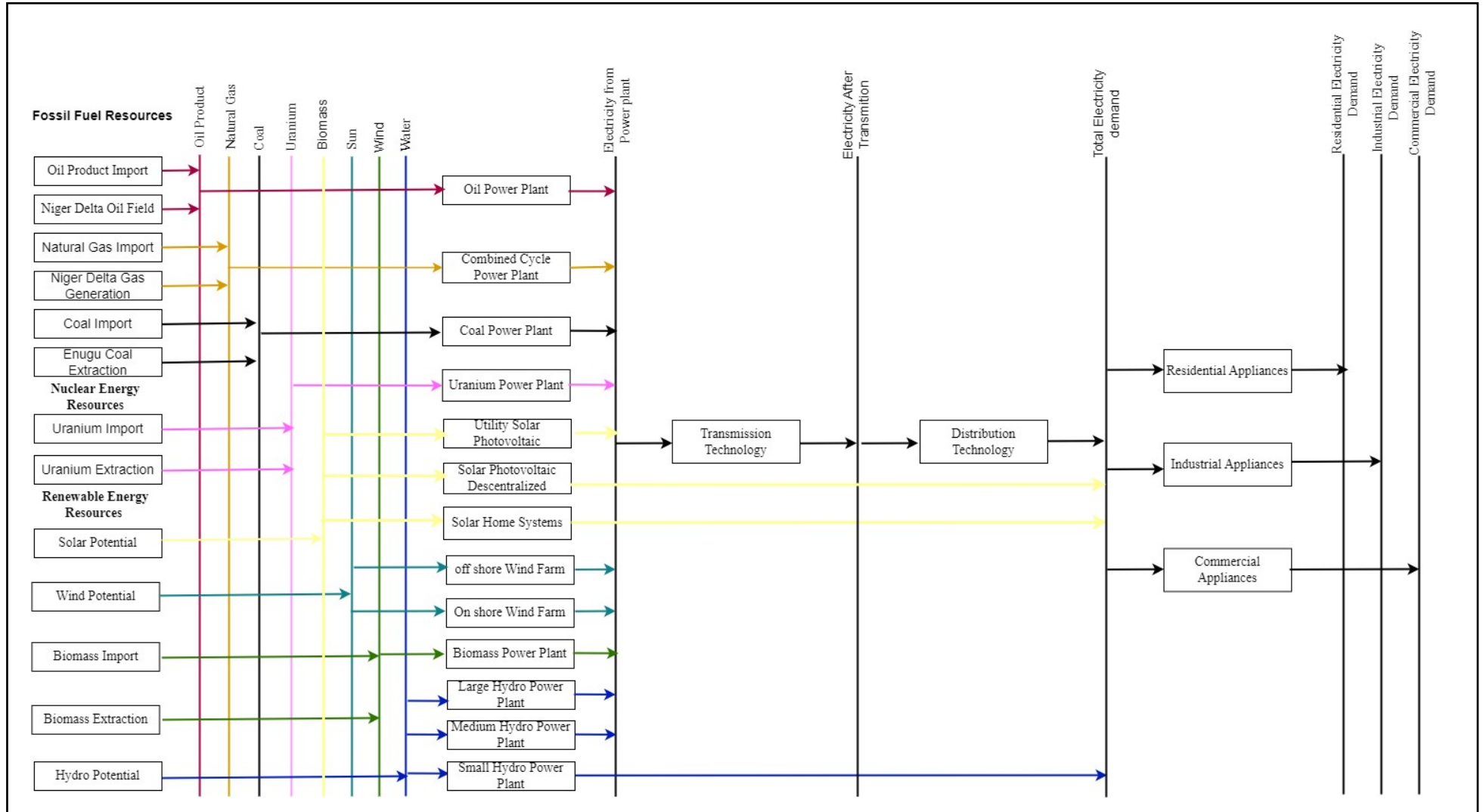


Figure 3. 2. The reference energy system of the model under study.

3.2.3.2. Research methodology and modeling procedure

The study's methodology is represented by the schematic flow chart shown in Figure 3.4. While the procedure aims to reduce the total actualized cost of energy generation over a selected time horizon and predicts the additional installations required along with the existing facilities to meet the energy demand it also shows the framework on which the model is built. At the same time, the role of renewable energy technologies and the cost of technology was evaluated by imposing suitable constraints on CO₂ emissions. The modelling procedure followed a three-step process: i) scenario inclusion; ii) data analysis; and iii) outcome.

I Scenario framework

The scenario framework suggests data types to input into the model while considering the study's objective. In this regard, three scenarios were considered including Business As Usual (BAU), Nationally Determined Contributions (NDCs), and a net-zero emission. To achieve these scenarios, input data are fossil fuel investments -such as diesel generators and natural gas -, hydroelectricity data, solar data, and emission data. The latter data are succinctly presented in Figure 3.3. Table 3.2 represents scenarios the study employed to explore low-carbon energy transition strategies for Nigeria. According to Table 3.2, three strategic scenarios were examined based on the Nigerian National Development Contributions and the Net-zero Energy Transition Plan:

A. The Business-as-Usual scenario (BAU). This scenario assumes that the technology mix in 2022 is maintained. It also assumes that 25% and 40% of electricity demand will be met by diesel generators and natural gas, respectively. More so, hydropower and solar energy will be met by 20% and 15% of electricity demand, in that order, while considering their current growth rate. This implies that there will be no strategic investments in other technologies in the future. Thus, this scenario is based on the current energy reality in the Nigerian power sector.

B. The NDCs scenario aims to achieve NDC targets by constraining its emissions target. As such, it assumes an increased share of renewable energy (RE) by constraining its annual emissions according to the Nationally Determined Contribution target (NDC, 2021b). In the NDC, 30% of on-grid electricity would be based on RE by 2030, and 45% by 2050 of which 12GW from large hydro, 3.5GW from small hydro, 6.5GW from solar photovoltaic, 3.2GW from wind; and

C. The net-zero scenario describes the Net-zero energy transition plan agenda (NETP, 2022). The scenario assumes net-zero emissions by 2060. Here, input data include emission data and data based on the energy transition plan.

Table 3. 2 Study scenarios.

Scenario Label	Scenario Descriptions	Key Assumptions
BAU	The technology mix of 2022 is maintained for the modelling period	Demand is ultimately supplied by 25% diesel oil, 40% natural gas, 20% hydro and 15% solar for the modelling period.
NDCs	Nationally Determined Contribution (NDC) emission targets	The carbon emission limit is set to decrease linearly by 402 MT CO ₂ e annually.
Net-zero	Energy sector emissions reach net zero by 2060	The carbon emission limit decreases linearly from present-day values to net zero by 2060

II. Data analysis

The study data analysis was based on constraint adjustment according to the selected scenario. For the BAU, constraints were considered on the specific annual demand for natural gas, hydro, oil, solar, and off-grid supply, while for the NDCs scenario, constraints were put on the annual emission limit. Also, the model period emission limit was constrained for the net-zero scenario.

III. Outcomes

Results from the OSeMOSYS' energy modelling framework were compared based on electricity production, annual GHG emissions, and capital investment from the three scenarios.

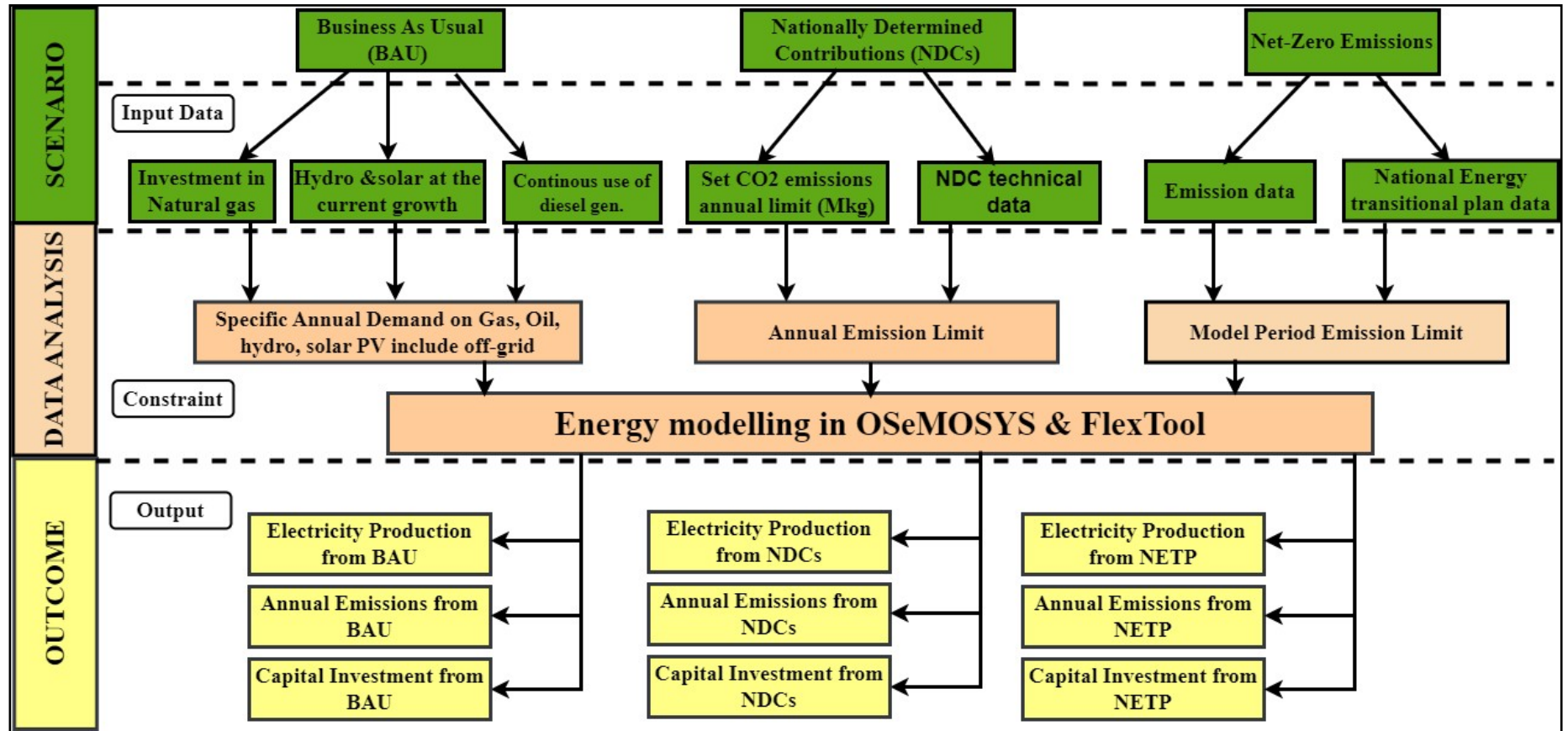


Figure 3. 3. Flow chart of study energy model buildup.

3.2.3.3. Procedure for adapting the Nigeria starter kit and SAND interface

Based on the study, the starter kit has been improved and adapted to suit the Nigerian power sector. To do this, the author adapts the starter kit model structure by updating data. This is to make the starter model more accurate and compatible with the Nigerian energy system. More importantly, the time slices represent periods of the year with a similar demand. For the model, the defined time slices depend on technologies' capacity factors and the specified demand profile. Meanwhile, the model employs demand for residential electricity, industrial electricity, and commercial electricity. While the capacity factor of technology is the same for non-renewable technologies such as coal power plants, the value varies for renewable power plants such as solar power. This is due to dispatch variability during the day and night.

The time slices were initially divided into 96-time slices which account for variations throughout hours and variations in energy from renewable technologies. Time slices are considered in two seasons – dry and rainy seasons, with day and night variations - Dry-season Day (DD), dry-season Night (DN), rainy-season day (RD), and rainy-season night (RN).

However, the time slices were reduced to 8 to make the model simulate much quicker on the computer. With 96 time slices, there is no significant variation in the data, which indicates that reducing the time slice to 8 does not negatively affect the modelling outcome. Equation (3.2.1) assumes each season has an equal length, with an average hourly split per season.

$$2 \frac{\text{Seasons}}{\text{year}} \times 4 \frac{\text{hour of representative day}}{\text{season}} = 8 \frac{\text{timeslices}}{\text{year}} \quad (3.2.1)$$

Each time slice represents an equal fraction of the year defined as the Year Split expressed in equation (3.2.2)

$$\frac{1}{8} \text{ timeslice/year} \quad (3.2.2)$$

Equation (3.2.2), therefore, represents the duration of each time slice for the year slip profile, which is added to the SAND interface. The value of 0.125 in equation (3.2.2) is, therefore, added to the year slip column for each year.

3.2.4. Results and Discussion

In this section, an overview is provided. Also, a comparative analysis of the aforementioned scenarios - the business as usual (BAU) scenario, NDC scenario, and net-zero scenario - is presented. The comparison is based on electricity production, annual CO₂ emissions, and capital investment.

3.2.4.1. Electricity production

Figure 3.4 shows electricity production across all three scenarios in 2030, 2050, and 2070, respectively. Using energy technologies for electricity production, the figure illustrates a comparison scenario. Note, that it is pertinent to reiterate that the OSeMOSYS model optimizes the energy system based on the least-cost approach. On this note, the model has selected the least-cost technology to meet electricity demand in the prescribed year.

In the first modelling period (2030), the BAU indicated that energy demand would be met mainly by electricity generated from light fuel oil, natural gas, and hydropower. Currently, this is the status quo in Nigeria as most electricity consumers depend on light fuel oil in the form of backup generators powered by diesel or premium motorspirit (petrol) to power their homes and businesses. This implies that the current electricity mix remains the same until 2030 in Business as Usual (BAU). Also, the NDC and Net-zero scenarios have a larger mix of solar photovoltaic electricity. The model recommends an energy mix dominated by solar to achieve NDC and Net-zero. However, light fuel oil is still used to meet some electricity demand in a Net-zero scenario.

For the second modelling period (2050), the model recommends an increase in solar energy share in the BAU scenario. However, it recommends a reduction in light-fuel oil use and an increase in natural gas share. This is in line with the current federal government agenda to employ natural gas as a transiting fuel. Over the past few years, solar energy sources, such as solar arrays, solar home systems, and solar lanterns have gained government and public attention. The model represented this claim in the BAU for 2050. This implies that solar energy resources will be used to provide clean energy in the Nigerian energy transition. Also, the model recommends solar energy to drive the NDC and net zero in 2050.

A similar trend was observed in 2050 and the 2070 modelling period. The 2070 modelling period shows an increase in solar energy resources in the form of solar PV, SHS. Also, the BAU shows an increase in backup generators, and net zero scenarios are likely to be achieved. However, the model recommends that solar energy will be the main source of energy in net zero with traces of hydropower. This implies that Nigeria's energy transition agenda has few renewable technology options.

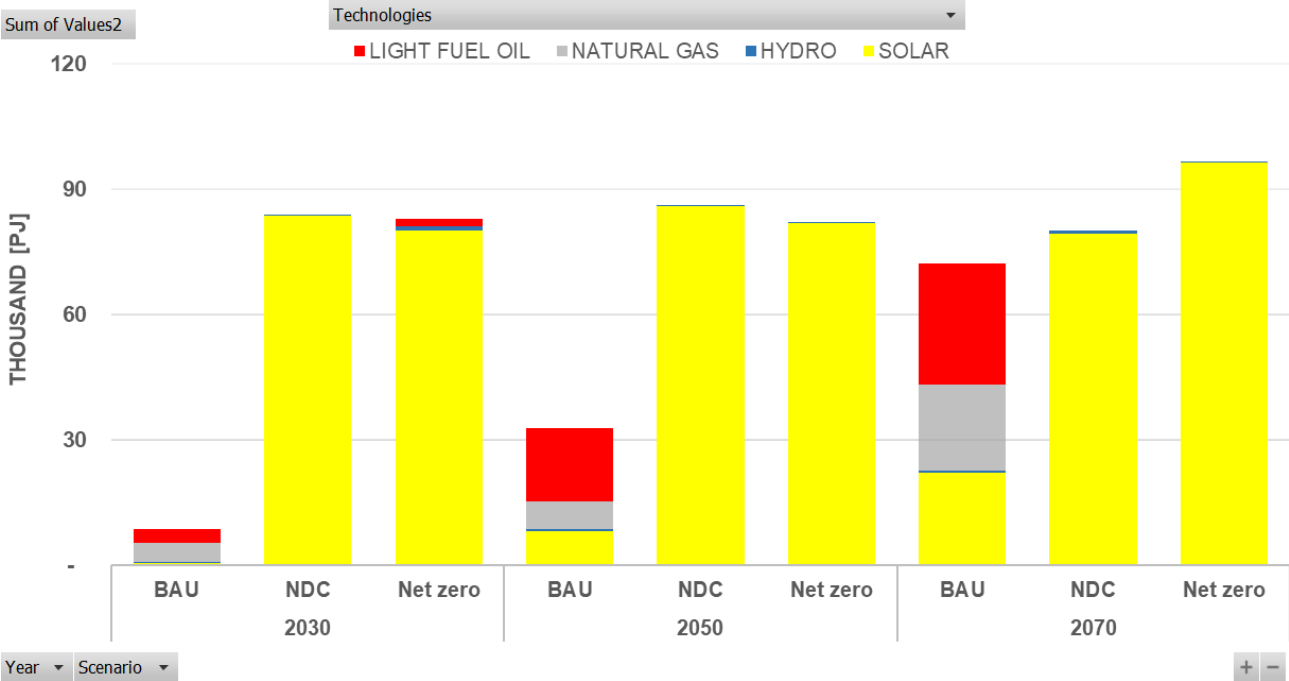


Figure 3. 4. Electricity production.

3.2.4.2. Capital Investment

The capital investment required to achieve the scenario across the modelling period is shown in Figure 3.5. The 2030 modelling period suggests no significant investment in the BAU. Also, the NDC represents about 5.2 trillion US dollars. In 2030, the NDC shows an increase of 33% over Net-zero this could imply that the investment required for achieving the NDC differs from that in Net-zero. Also, the 2030 timeline is strategically defined as a sustainable year as compared to the net-zero agenda. Solar energy will experience significant investments, with the largest investment in 2030.

For the 2050 and 2070 modeling period investment follows the same trend and pattern, despite relatively low investment in natural gas and light fuel oil in the BAU. The average annual investment is \$66Bn for BAU, \$190Bn for NDC, and \$155Bn for Net- zero.

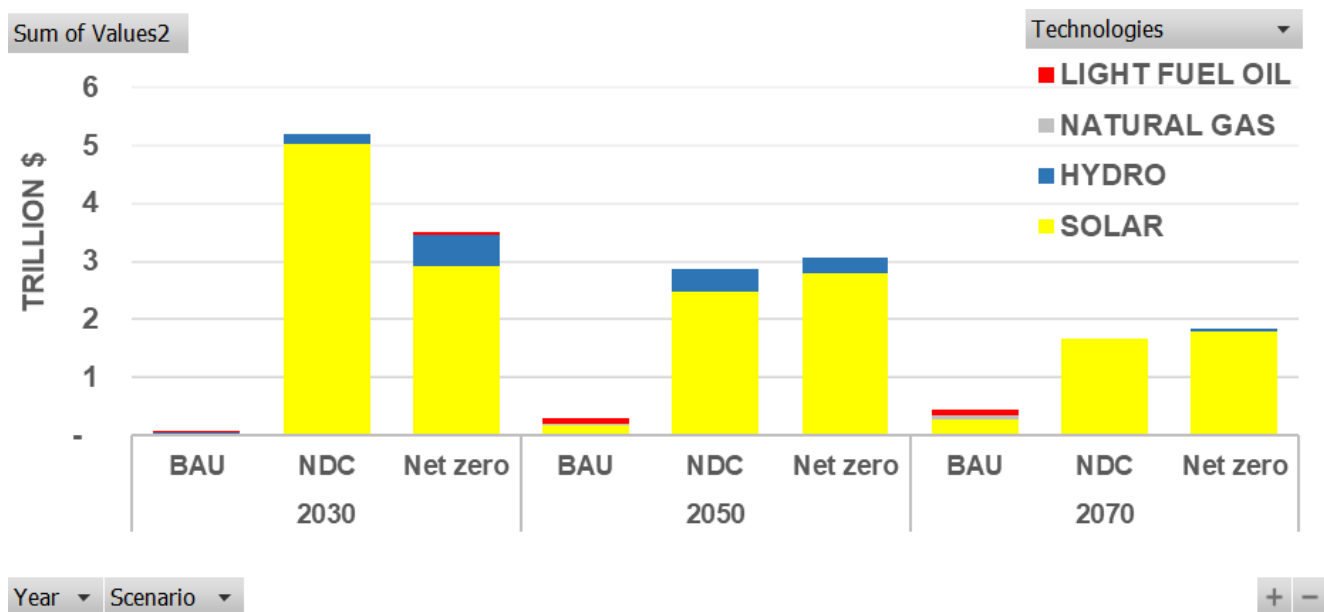


Figure 3. 5. Capital investment.

3.2.4.3. Annual Carbon-dioxide emissions

Figure 3.6 depicts CO₂ emissions from three scenarios. The BAU scenario shows an increasing emissions trend, while the NDC and net-zero scenarios reveal decreasing patterns. Compared to net zero scenarios, the NDC scenario shows a steeper decreasing emission rate by 2060 as a result of the net-zero constraint considered in the model. Both emission scenarios, however, are expected to converge by 2060. The model recommends that net-zero emissions will be achieved along the paths, while the BAU did not converge, but experienced a significant decrease in 2040. BAU emissions remain above 1 million MKg of CO₂ equivalents, but the NDC has a more ambitious emission reduction trajectory.

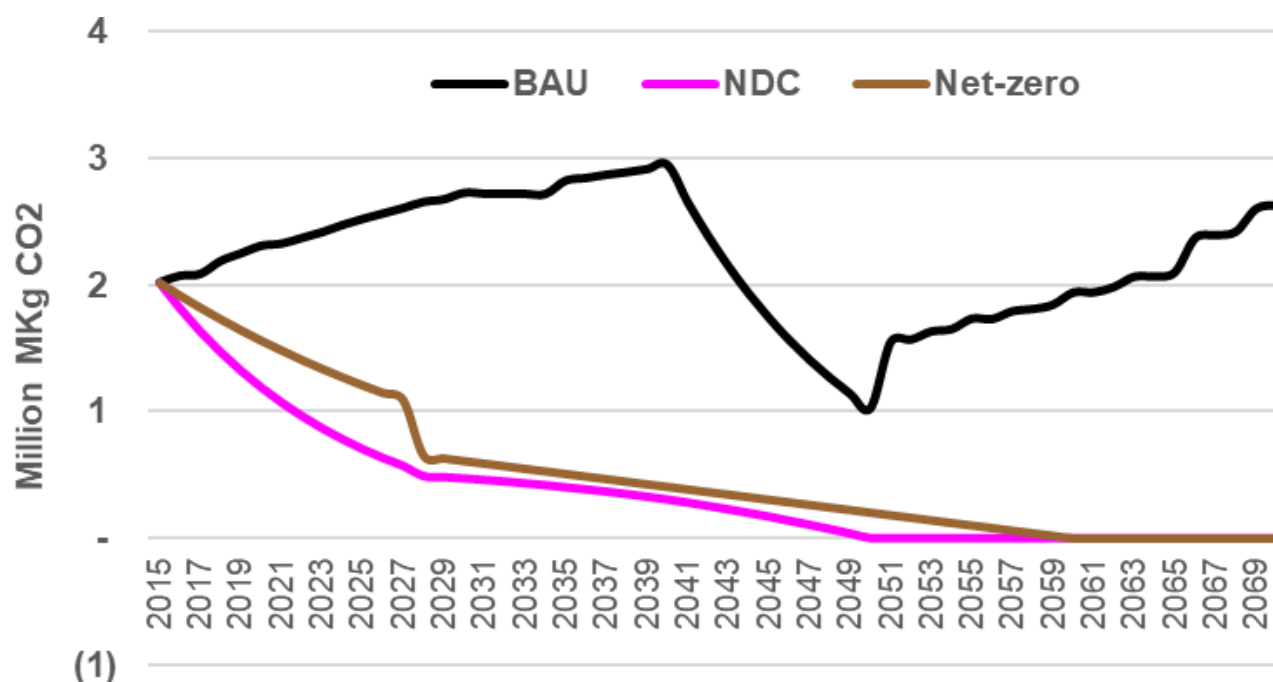


Figure 3. 6. Annual Carbon-dioxide emissions.

3.3. Modeling Energy Efficiency Pathways

3.3.1. Modeling Background

As part of the analysis of stakeholders' perspectives, energy efficiency plays a crucial role in the Nigerian transition outlook. Because energy efficiency has the potential to reduce electricity demand and emissions, the OSeMOSYS' modelling framework has been employed to explore the energy efficiency of the Nigerian energy transition plan. Although the National Renewable Energy and Energy Efficiency Policy (NEEEP), NDC, and the Nigeria Energy Transition Plan (NETP) have a plan to engage energy efficiency across the energy sector in Nigeria (NEEEP, 2015; NDC, 2021a; NETP, 2022). However, there is no clear pathway to achieve energy efficiency pathways to enhance net-zero emissions ambition as they are separate national policy and energy planning documents. Thus, there is no coherence between energy policy documents.

The current sub-section will explore energy efficiency pathways for the Nigerian energy transition plan based on the OSeMOSYS modelling framework (refer to (Golobish *et al.*, 2022)).

To achieve this, the least cost system optimization model in OSeMOSYS was used to explore energy efficiency in the Energy Transition Plan and NDCs, this is informed by a study conducted in literature (Barnes *et al.*, 2022; Cannone, Allington, De Wet, *et al.*, 2022).

The Standard Organization of Nigeria (SON) has developed the Nigerian Energy Label Guide (NELG) for Air Conditioners (ACs), freezers, solar off-grid appliances, and electrical appliances (Gbadeyanka, 2017; Olowookere, 2017). The guide label is rated from 1 to 5, where 5 indicates the highest energy efficient level and 1 represents the lowest. To adopt the energy label in the OSeMOSYS ClicSAND model, the current study has adopted a three-tier energy efficiency level, which is categorized into three levels: i) Standard efficiency appliance; ii) Good efficiency; and iii) Deep efficiency levels of energy-efficient appliances. This adoption was done according to their usage in the residential, commercial, and industrial sectors. The energy rating adopted from the NELG represented labels 1 & 2 as standard efficiency, label 3 as good efficiency, and 4 & 5 as deep efficiency standard, accordingly.

- i. **Standard efficiency (SE) appliance.** This category refers to energy-efficient labels based on the Nigerian Energy Labels 1 and 2. This implies that the status quo in the usage of low-energy efficiency appliances is maintained;
- ii. **Good efficiency (GE).** It implies that more energy-efficient appliances are considered compared to the standard efficient appliances. Further, GE represents the third label in the NELG standard;
- iii. **Deep efficiency (DE).** It suggests that appliances have complied with the highest standard of efficiency rating which is labels 4 & 5.

3.3.2. Energy Model Framework and Assumptions

Here, the energy efficiency modelling framework is explained. The framework is summarized in Figure 3.7. The latter figure depicts 1) scenario development, where model assumptions are considered; 2) Data analysis, where the model is constrained; and 3) the results, where the model outcome is visualized.

This subsection also intends to answer the research question "How can electricity demand and emissions be reduced through energy efficiency?" To answer these research questions, three scenarios were developed, represented in Table. 3.3.

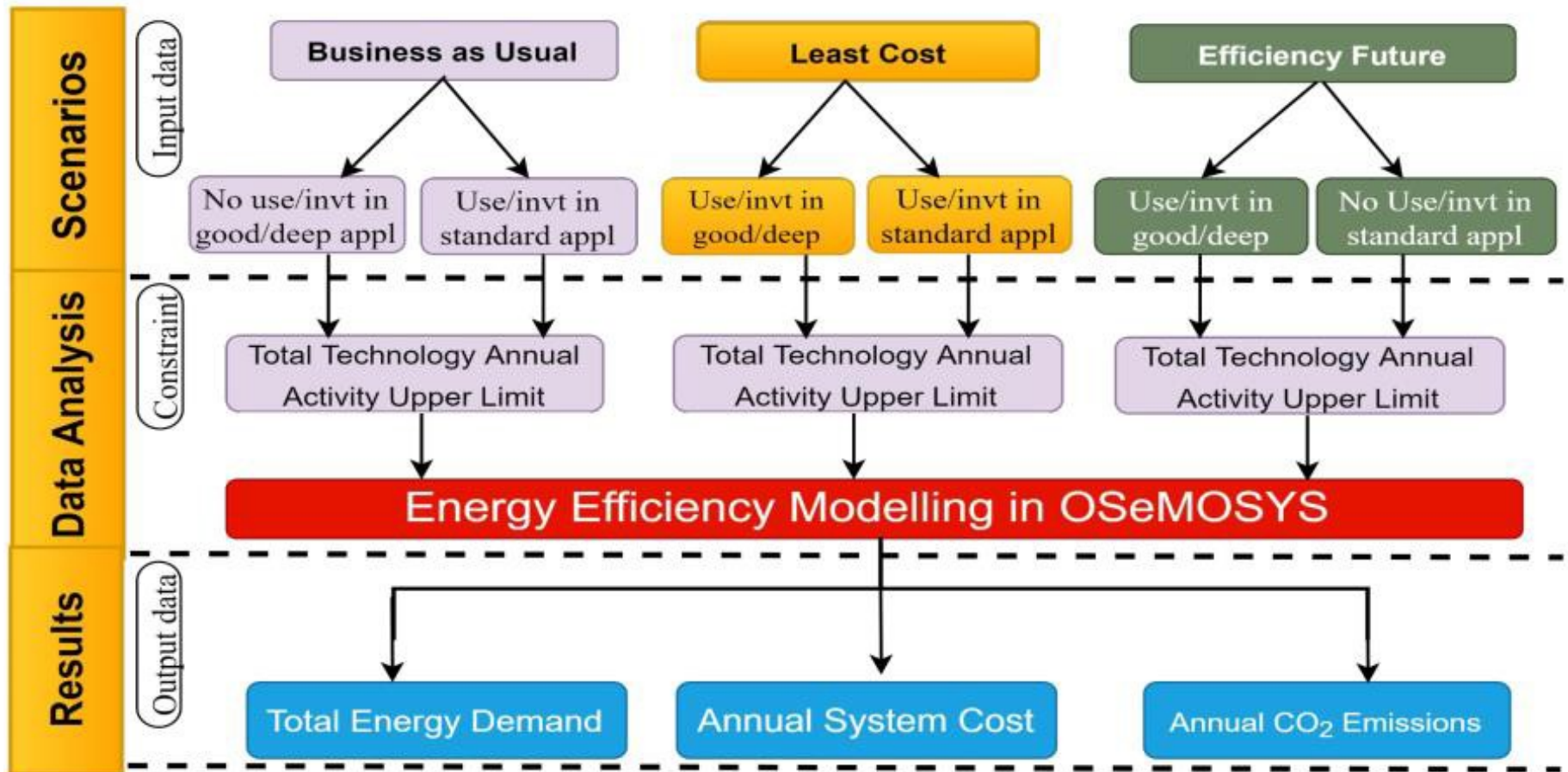


Figure 3. 7. Energy modelling flowchart and study scenario framework.

3.3.2.1. Scenario development

Part of the energy efficiency model framework is to develop the sub-study model assumptions. To answer the research question, three scenarios were developed in the OSeMOSYS model (Figure 3.3) based on the Nigeria Energy Label Guide (NELG).

The first scenario describes no investment in energy-efficient appliances except the status quo, which means only standard efficiency appliances. This scenario assumes that there will be no impact on the energy efficiency of appliances or devices unless deliberate policy implementation efforts are enforced. While the second scenario, referred to as the least-cost scenario is described as a build-up from the previous scenario in such a way that investment is made in the energy efficiency of all technology across all labels - standard, good, and deep. This means that there are significant opportunities to invest in energy efficiency driven by minimizing system costs. In the efficient future scenario, it assumes that there will not be investment in standard efficiency appliances, but rather good and deep appliances. On this note, this scenario assumes that there are greater chances of upgrading all electrical appliances in Nigeria to either good or deep or both efficiency standards.

Table 3. 3 Energy efficiency standard scenarios.

Scenario Label	Scenario Description	Key Assumption
Inefficient future	No investment in energy efficiency; only investing in standard efficiency appliances	Significant investment in energy efficiency will not happen without policy interventions
Least cost	Unconstrained model relative to BAU and Efficiency future with cost optimization. Investment is allowed in all levels of efficient appliances (standard, good, deep).	Significant opportunities for investment in all energy efficiency appliances driven by minimization of the system costs
Efficient future	No investment in standard efficiency appliances; only investment in good and deep appliances	It is possible to upgrade the efficiency of all appliances in the nation to good or deep efficiency

3.3.2.2. Data analysis

Data analysis has been simplified to avoid modelling complications. The Total Technology Annual Activity Upper Limit (TTAAUL) is constrained. The TTAAUL according to OSeMOSYS ClicSAND is the total maximum level of technology activity in one year. This implies that energy efficiency across all levels/labels and sectors has been pegged at a maximum level of activity of investment. There will be no further investment and activity beyond these thresholds.

3.3.3. Results

The modelling outcome showed the result obtained from each of the scenarios. Scenario results are presented based on: i) Total energy demand; ii) Annual system cost; and iii) Annual CO₂ emissions.

3.3.3.1. Total Energy Demand

The total energy demand from the three scenarios is compared in Figure 3.8. The cumulative demand over the modelling period is 19,000 PJ or 600 GW lower in the Least Cost and Efficient Future scenario. This means that with energy efficiency efforts, power savings of 600 GW will be achieved. These savings imply about a 37 percent reduction in total energy demand compared to the inefficient scenario. In contrast, about 468 PJ of total energy demand is lower in the efficient future than in the least-cost scenario.

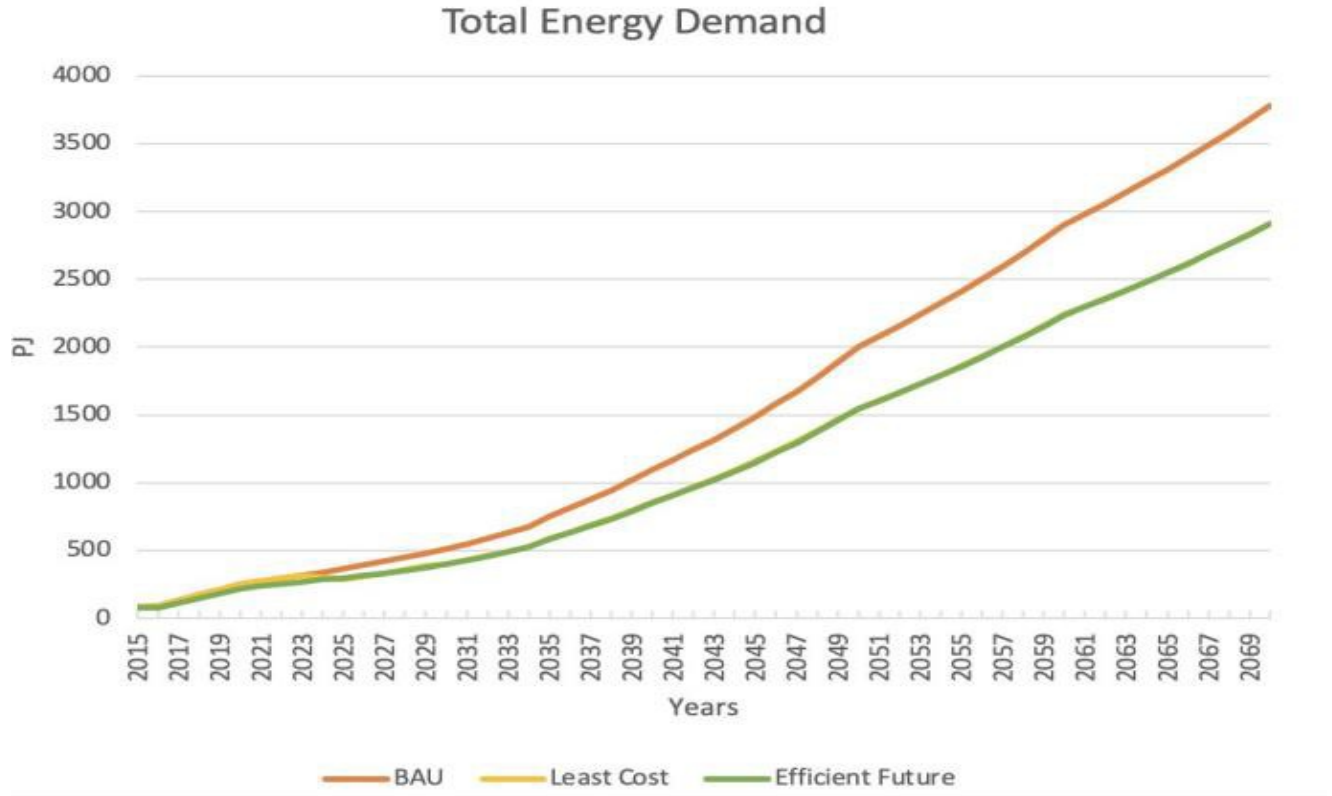


Figure 3. 8. Energy efficiency and total energy demand.

3.3.3.2. Annual system cost

Figure 3.9 shows the annual system costs energy efficiency. The annual system cost revealed a similar trend across all scenarios. However, the BAU was expected to incur the highest system cost in the future, such that a cumulative cost of about 1.4 Trillion USD and 3.1 Trillion USD would be saved from the Least Cost scenario and Efficient Future scenarios, respectively, in the modeling period. Also, the high costs in the BAU scenario in the later part of the model period suggest that appliances are heavily discounted when considering total system costs.

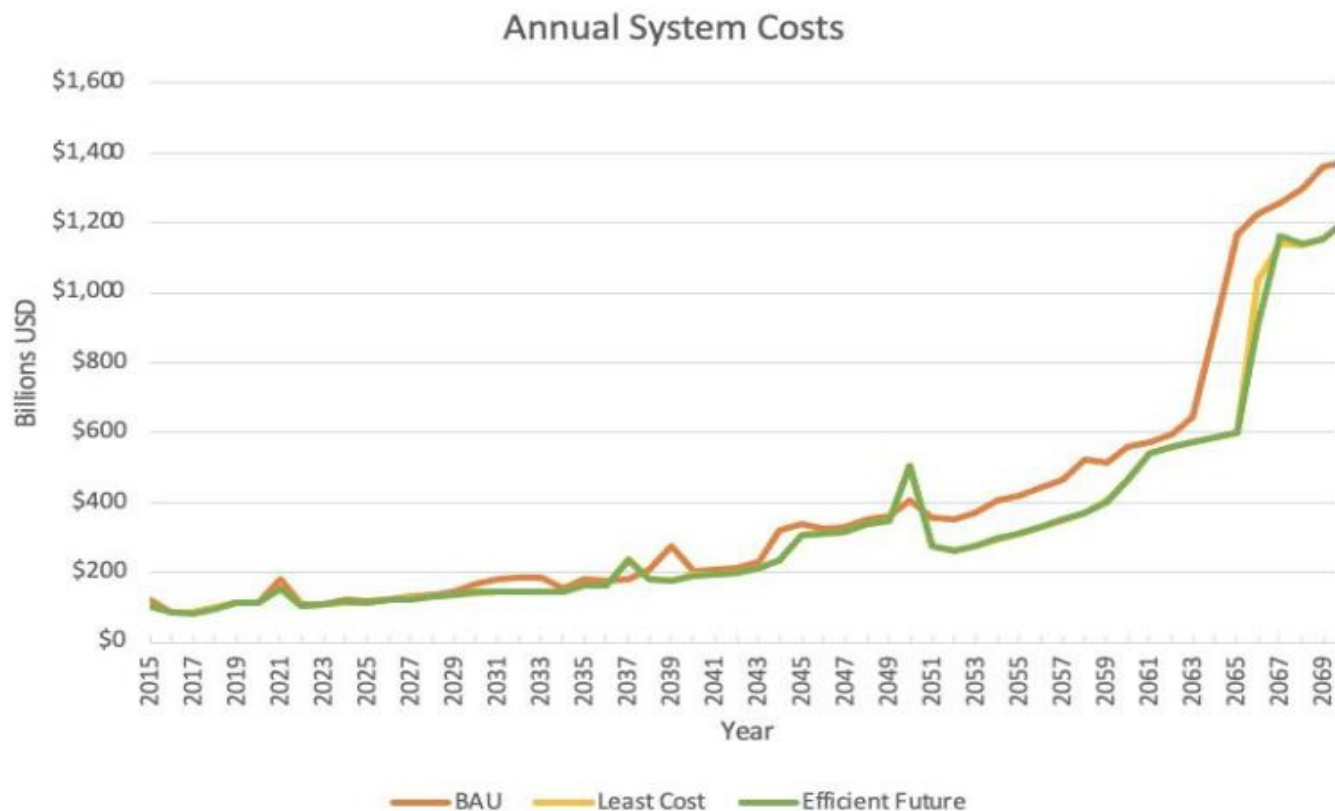


Figure 3. 9. Energy efficiency and annual system cost.

3.3.3.3. Annual CO₂ Emissions

Figure 3.10 shows the impact of energy efficiency options on carbon emissions. Based on the figure, emissions remain constant across all scenarios until 2039, when a sharp decrease occurs. Annual carbon emissions will increase in 2050. However, the Least Cost and Efficient Future scenarios ultimately produce savings of 72 and 75 billion tonnes of CO₂, respectively compared to the BAU. This is coupled with an 11.42% decrease in emissions over the modelling period.

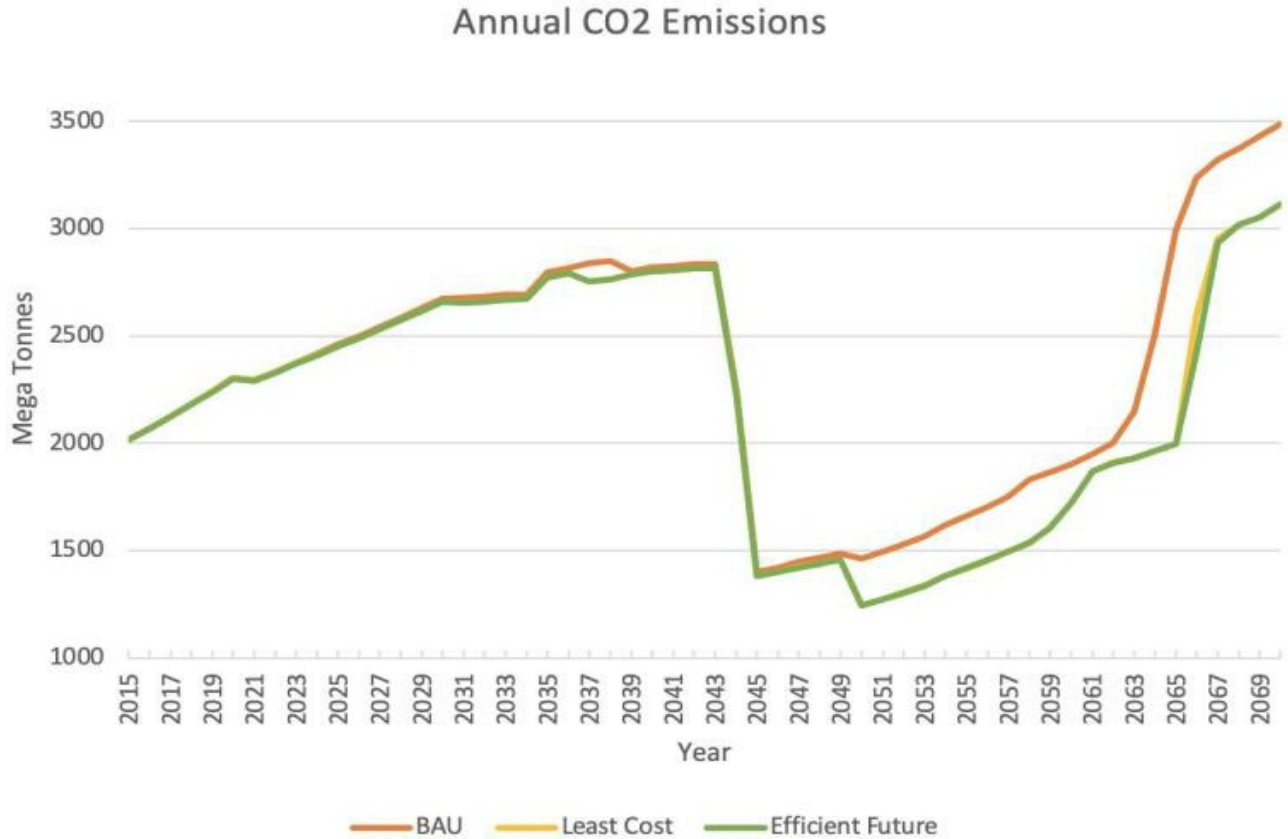


Figure 3. 10. Annual CO₂ emissions based on energy-efficient appliances.

3.3.4. Conclusion and recommendations

The conclusion section of the current chapter describes the deduction/take-home from the analysis and compatibility assessment of open-source modelling. This description is compatible with modelling a developing country's energy sector. It also presents a case where one of the compatible models is applied to investigate Nigeria's energy transition pathways. Also, this sub-sector will present some policy insights based on the resulting outcome.

a. Compatibility of an open-source model

The research in the subsection aimed to conduct a compatibility assessment of open-source energy modelling tools to investigate low-carbon energy development, considering the dynamics of developing countries' energy systems. Based on the qualitative and some suitability criteria a comparison assessment was done on some selected open-source energy modeling tools. It can be concluded that OSeMOSYS, PYPASA, and OEMOF are, respectively, the most suitable and compatible tools to address future low-carbon energy analysis for developing countries cases.

The results indicated that open-source energy modelling tools are not only relevant to providing insights for developing countries' low-carbon transition but also countries can own their modelling experience without the interference of external stakeholders. This suggests that the process of modelling low-carbon and net-zero emissions strategy would be made affordable, transferable and transparent.

This study has clearly illustrated that open-source energy modelling tools employ and are guided by the transparency modelling principles summarized in U4RIA but also raises the question of temporal and spatial resolution compatibility issues due to granular data dearth (i.e., hourly demand data) in the region. Hourly data could be collected through surveys.

b. The case of the OSeMOSYS application

The OSeMOSYS model based on the ClicSAND model is applied to model a typical developing country. The Nigerian power sector was examined as a case study. Its electricity generation, the economy through capital investment, and the environment through carbon dioxide emissions were investigated. Three scenarios were developed to investigate Nigeria's clean energy transition. The study concluded that solar energy will be Nigeria's clean energy fuel in the future to achieve net-zero emissions. The results indicated that energy access would be achieved using a solar energy intervention. In addition, emissions would be cut to zero in the net-zero scenario compared to BAU.

3.3.4.1. Recommendation and policy insights

Based on the findings and conclusions presented the following recommendations are suggested:

- i. Since the compatibility and comparison analysis of selected open-source tools has been conducted, scientists, researchers, and practitioners in the energy space, should embrace the use of open-sourced modelling tools to gain insight into clean energy transition pathways and evolution. Also, improvement to the modelling tool by the principal developer or other developers should be considered to capture the most relevant characteristics and attributes of developing countries' energy situations. In addition, the synergy between energy modellers and developers is critical. This synergy would enable model developers to know exactly the energy situation and asymmetrical nature of developing countries. Efforts should be put together to train and retrain model users in the form of capacity building to get more local modellers involved in national/country energy modelling activities.
- ii. The application of the model is exemplified by the OSeMOSYS model. This has revealed

that solar energy intervention will enable achieving climate goals faster. As such, investment and attention should be directed to solar energy resources and interventions. These include solar mini-grids, solar home systems, and other ancillary parts of solar energy. Also, research should be conducted to understand the main market tools that drive solar energy adoption and utilization among Nigerians.

- iii. Energy-efficient appliances play a key role in energy efficiency for demand-side management. This means that investment in energy-efficient appliances would not only cut emissions but also lower users' utility bills and enable substantial returns on solar energy investment. Thus, government agencies in charge of energy efficiency implementation should devise sustainable strategies that will enforce the use of efficient appliances in the household/residential, commercial, and industrial sectors.

CHAPTER FOUR

LOW-CARBON ENERGY SYSTEM MODELING FOR ENERGY TRANSITION PLAN: AN OPEN ENERGY FRAMEWORK APPLICATION (OEMOF)

4.0. Introduction

This chapter employs OEMOF to explore a system analysis and the role of green hydrogen technologies as a future energy carrier in the Nigerian power sector. This application supports low-carbon development and climate goals. It also considers the outlook and potential of green hydrogen as a future low-carbon fuel along with other technologies in the Nigerian energy mix. It explores how energy demand would be met across several suppressed demand scenarios through a distributed generation strategy. To do this the study utilized secondary data mined from national and international archives, a national energy master plan, reports, Nigeria's demand profile extracted from global load projection presented in Toktarova *et al.* (2019), and insight from the analysis of stakeholder perspectives on the Nigerian energy evolution published by Shari *et al.* (2023).

4.1. Background and green hydrogen technology

In recent years, many countries, including Nigeria, have committed to net-zero emissions in their energy sector. Their net-zero target is intended to cut about 88 percent of global greenhouse gas emissions, and it is expected that an ambitious net-zero emissions target, capable of keeping global temperature increases to within 1.5°C (IPCC, 2018a). This ambitious climate goal means striking a balance between GHG emitted to the atmosphere and removed GHG. Emissions from all energy end-users must be reduced to reach this target. While energy efficiency, electrification, and renewables can achieve 70% of the global mitigation needed as an orderly transition in the energy sector, hydrogen will be needed to decarbonize end uses where other options are less mature or more costly (IRENA, 2022). Considering these applications, hydrogen could contribute about 10% of the mitigation needed to keep the global temperature increase to within 1.5°C (IEA, 2021b).

Hydrogen, in itself, is not an energy source but an energy carrier, which can be produced from multiple feedstocks, such as fossil fuels and renewable energy sources, through electrolysis (shown in Figure 4.1). Apart from electrolysis, that is, the splitting of water molecules, there are other methods of producing green hydrogen include the decomposition of natural gas, solar hydrogen production, biological hydrogen production, and thermos-chemical splitting³⁶.

However, the aforementioned methods of producing green hydrogen have yet to be commercialized. Currently, hydrogen is produced on a commercial scale from fossil fuel sources and can be used across virtually any application at the industry scale – steel and chemical industry & in refinery, transport, heating, and power generation (Gielen *et al.*, 2020).

Figure 4.1 shows electrolytic hydrogen represents a meager share of global electricity generation by source. This suggests that hydrogen production from renewable energy sources is largely experimental. In 2021, electricity generated from renewable energy accounted for about 33% of global electricity generation. This means that only about 1% of hydrogen output is produced from renewable energy. The implication is that electrolytic hydrogen remained limited, at about 700 MW in 2021 (IRENA, 2022).

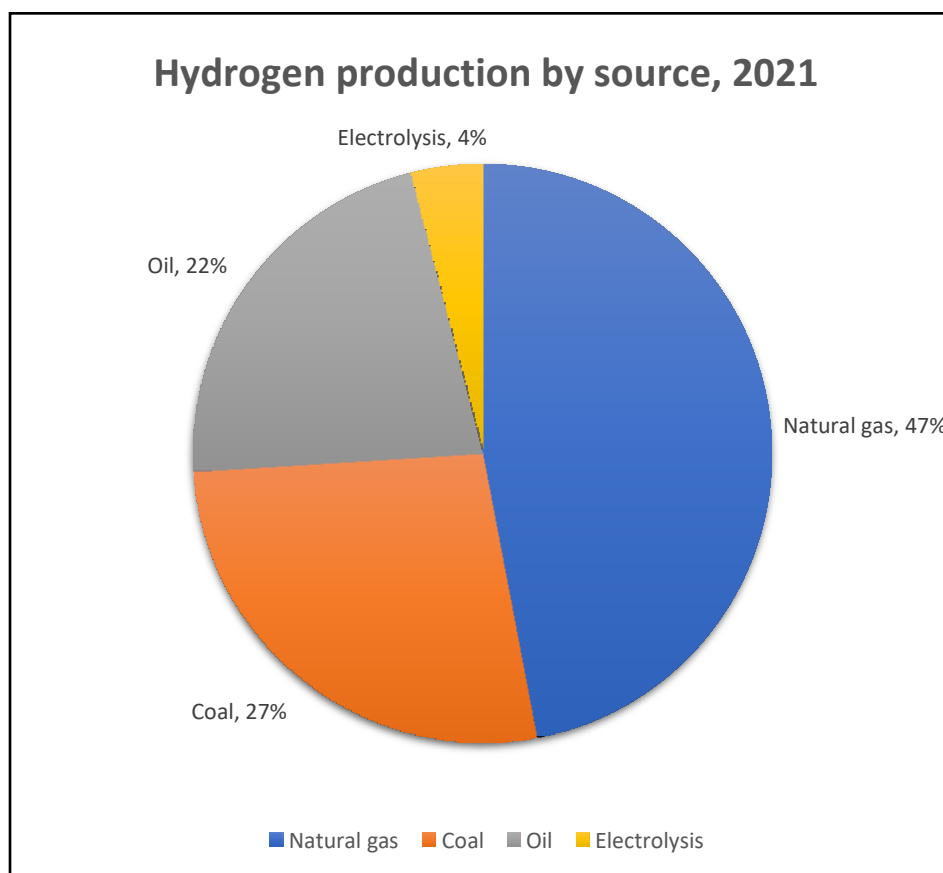


Figure 4. 1 Hydrogen production by source in 2021. (Data source: IRENA, 2022).

³⁶<https://www.futurebridge.com/industry/perspectives-energy/green-hydrogen-generation-overview-of-upcoming-technologies/>

Hydrogen production from renewable sources - green hydrogen or electrolytic hydrogen - is considered a potential source of a sustainable future and may unlock the global renewable energy trade. As a result, electrolytic hydrogen can also enhance sustainable CO₂ capture when CO₂ reacts with hydrogen, which in turn forms synthetic fuel and acts as a reducing agent to replace coal in iron production (IRENA, 2022). Also, nitrogen being a main component of greenhouse gases when reacted with green hydrogen produces green ammonia which can be used as feedstock for green fertilizers. This means that the hydrogen needed to make ammonia will come from water using electrolysis based on renewable electricity (Ramachandran & Menon, 1998). The hydrogen derivatives produced further enhance hydrogen energy density, making long- distance transport and long-term storage cost-effective (Di Lullo *et al.*, 2022; HFW, 2022). For instance, liquid ammonia has almost eight times the energy density (MJ/m³) of lithium-ion batteries and more than 20 times the gravimetric energy density or specific energy (MJ/kg) (IRENA, 2022).

Embracing worldwide and national adoption of several hydrogen derivatives would reduce global dependency on fossil fuel resources. This would likely enable the timely attainment of global and national energy transition targets. Global energy trade through hydrogen derivatives would provide economic benefits as importing countries can tap into cheaper (than domestic) resources, improving the resilience of the system since there are alternative ways to satisfy final energy demand, and hence strengthening energy security. Also, the development of green hydrogen and associated derivatives is significant in enhancing a circular economy and creating green jobs while meeting international and national energy demand (Štuller *et al.*, 2022; Kabir *et al.*, 2023). Further, most developing countries are heavily dependent on fossil fuels despite having high renewable potential. On this note, Panchenko *et al.* (2023) claimed that investment in hydrogen derivatives could tackle energy insecurity, accelerate green electricity production and improve renewable energy resources exploitation (Panchenko *et al.*, 2023)

Concerning the present and foreseeable energy future, hydrogen could have several attributes and benefits on a global and national scale. It is therefore imperative that developed and developing countries embrace hydrogen as a future fuel and position themselves at the technological frontier. This will enable them to take full advantage of her carbon neutrality targets. These opportunities are in power generation, heat for industry, transportation, storage, and low-carbon Hydrogen (IRENA, 2023).

The abundance of renewable energy resources in sub-Saharan Africa implies that countries in the West African corridor can harness the potential of hydrogen fuel cells to light up our homes and businesses, and even support the global climate neutrality agenda (Baye *et al.*, 2021).

The abundance of solar thermal power potential in Nigeria, estimated at over 427 GW and an average of 6,372,613 PJ/year of solar energy, is received in the entire country (Ohunakin, 2010; Newsom, 2012). Also, water resources comprising surface water of about 267 billion cubic meters and enormous groundwater resources estimated at 52 billion cubic meters of replenishable yield per year and existing in basement complex which covers over 60% of Nigeria (Oteze, 1981; Maduabuchi, 2004; Newsom, 2012; USAID, 2021). These and many more are among the numerous energy resources found in Nigeria. The availability of these enormous renewable resources indicates that the country has the capacity required for natural feedstocks for electrolytic hydrogen fuel cells. This is an opportunity for Nigeria to generate alternative energy to cater for the demand of the growing population by complementing the existing technologies to attain energy sufficiency and economic growth.

While hydrogen alone cannot halt climate change, its high energy content per unit weight compared to gasoline or diesel is an excellent clean future fuel cell in the energy mix that could help ameliorate climate impacts. It is, consequently, an effective alternative energy fuel in the power sector, heavy industries, and transport sector. Therefore, it tends to drive the low carbon agenda in the net zero transition plan. Nigeria should therefore recognize the need to position itself at the technology frontier to take full advantage of the energy transition opportunities. These opportunities are in the production, transportation, storage, and use of renewable hydrogen.

Several challenges confronting Nigeria's power sector, including unavailability of gas, machine breakdowns, seasonal water shortages, and limited grid capacity, have severely limited the operational performance of power generator plants (Roche *et al.*, 2020). This situation has led to acute shortages of electricity supply across the country with blackouts lasting for several hours in a day. Despite challenges confronting the energy sector, Nigeria is committed to achieving net zero by 2060. The plan presents an opportunity for Nigeria to generate alternative energy to cater for its growing population and attain energy sufficiency and economic growth. In addition, it will create legitimate well-paying green jobs (NETP, 2022).

In August 2022, Nigeria officially launched its Net-zero transition plan (NETP) aimed at changing energy production and use, with increased removal of greenhouse gases from the atmosphere while improving electricity access. It also includes plans to integrate green hydrogen into her energy mix as a potential future clean fuel cell. Outlined strategies include but are not limited to i) generating electricity without emissions; ii) using electric vehicles; iii) deploying carbon capture and storage, and direct air capture; and utilizing hydrogen as an alternative fuel, among others (NETP, 2022).

Although the Nigerian Government has presented a clear pathway to meet demand across the centralized and decentralized power area, it has not explored in detail the role of green hydrogen as a future energy carrier in the net-zero emissions target. Against this backdrop, the study in this chapter aims to explore the prospects and dynamics of green hydrogen in the Nigerian energy transition plan. It also assesses different decentralization strategies that meet suppressed demand

To examine hydrogen utilization and decentralization strategies in the Nigerian power sector the following research questions are considered.

- A. How will suppressed demand be met in an energy mix with different net-zero emissions targets and different energy mixes including renewable energy, hydrogen fuel cells, and nuclear?
- B. What energy mix would be deployed to fully decentralized pathways for the Nigerian power sector?

To achieve this, the study in this chapter explores a distributed assessment of green hydrogen production among five Electricity Distribution Companies (DisCos), from three geopolitical zones in Nigeria – North West, North Central, and North East. Also, scenarios that consider fuel switching, energy efficiency, nuclear, and investment in renewable energy both on-grid and off-grid are considered. This implies that a dual modelling approach would be applied based on i) a system thinking approach from a stakeholder's perspective analysis by Shari et al., (2023), and ii) a bottom-up optimization linear programming methodology based on an open energy modelling framework (OEMOF) was used as the modelling paradigm.

This chapter is organized as follows: sub-section 4.2 reviews the state of the art of green hydrogen and its application in developing countries and Nigeria, 4.3 discusses the methodology, including OEMOF application to system analysis of green hydrogen, final sub-section presents results and discussion from the analysis, the chapter presents the results and discussion in sub-section 4.4 while

sub-section 4.5 concludes the chapter with recommendations.

4.2. The Role of Hydrogen in the Nigerian Power Sector

In the past hydrogen was only considered a fuel cell for transport, heat, and industries. Recently, developed and developing countries have embraced hydrogen fuel cells as a major part of their net-zero emissions strategy. Additionally, hydrogen end-use technology and its application demonstrate that the hydrogen economy is crucial to achieving net-zero-emissions targets both in developed and developing countries (van der Spek *et al.*, 2022). Hydrogen energy density (earlier discussed) has made hydrogen a significant source of energy in major heat-dependent sectors.

The world's investment in hydrogen as a future low-carbon fuel is not farfetched. These efforts could be attributed to some of the following benefits: 1) compatibility with conventional diesel or gasoline trucks; 2) hydrogen energy density – diesel has an energy density of 45.5 MJ/kg slightly lower than gasoline of 45.8MJ/kg in contrast, hydrogen has an energy density of about 120MJ/kg. In terms of electrical power, this implies that the energy density of a hydrogen fuel cell is equivalent to 33.6 kWh of usable energy for 1 kg compared to diesel or gasoline which is about 12-13 kWh per kg (Molloy, 2019); 3) high efficiency: 50% of the energy generated by an internal combustion engine converted as heat, while electric drive train powered by hydrogen only loses about 10% to heat; 4) while hydrogen stands better chances in price reduction of more than 50% lower than diesel in the next decade the price of fossil fuels is unstable and might not decline coupled with the Russia-Ukraine issues. Considering all these factors and more, there are better chances for hydrogen to gain the attention of world leaders as a main energy vector to achieve their carbon neutrality ambitions as it is an efficient, cheaper and economically sustainable future energy carrier.

Although electricity from hydrogen comes with its limitations including i) hydrogen gas is a colourless and odourless gas, and highly flammable, so detecting leakages could occur unnoticed and could be disastrous; ii) unclear pathways to the production of green hydrogen or renewable hydrogen; iii) there are still unclear pathways to which the technology of producing renewable could be scaled in the future as the technology is yet to be fully explored on a larger scale; iv) storage is another main limitation. Hydrogen is produced in gaseous form and needs to be pressurized or liquefied directly which requires more energy. However, there are emerging methods that use chemical bonds called liquid organic hydrogen carriers (LOHC) or ammonia to transport hydrogen in a stable state. These methods do not require pressure or cryogenic

liquefaction and thus utilize less energy to transport and store hydrogen, although the technology is still in the pilot stage (Molloy, 2019). Despite the overwhelming limitations of hydrogen, there is light at the end of the tunnel for hydrogen as the costs of renewable electricity needed to produce green hydrogen are falling and so are the costs of electrolyzers that split water into hydrogen and oxygen.

Although the use of hydrogen, as feedstock in industries has been well-established for over six decades (Fan *et al.*, 2021), green hydrogen is currently widely researched as a fuel cell for cars, producing fertilizers and electricity, it has recently emerged as a potential solution to decarbonize heavy transport because it releases almost three times the energy of what can be obtained from gasoline/petrol or diesel (Molloy, 2019). From a broader perspective, the world is making frantic efforts to produce, utilize, and commercialize electrolytic green hydrogen due to the benefits it offers as a decarbonization solution to the industrial, chemical and transportation sectors.³⁷ The European Union (EU) identifies the role of green hydrogen to achieve its climate targets and help reduce CO₂ output from sectors difficult to decarbonize, in this light, the European Green Deal (EGD) recognize hydrogen as key to a clean and circular economy.³⁸ It is indeed pertinent to know that plans to invest in hydrogen fuel cells have recently gained momentum in SSA countries, as countries are reviewing their energy acts to include renewable energy sources in their energy mix, including green hydrogen in their energy mixes (Kobina & Stephanie, 2022; IEA, 2022). For example, in 2021, Namibia announced an estimated 9.4 USD billion green hydrogen project by 2026.³⁹

Further, there is evidence that investment in green hydrogen is veritable; several European Union countries have signed a treaty with some West African countries to trade hydrogen fuel cells. The treaty to develop green hydrogen is unprecedented and has the potential to open up the green hydrogen fuel cell market of the ECOWAS region in the future. For instance, the German Ministry of Education signed a treaty with Niger to generate and export green hydrogen in the region (Bhandari, 2022).

³⁷<https://www.weforum.org/agenda/2021/06/4-technologies-accelerating-green-hydrogen-revolution/>

³⁸<https://www.intereconomics.eu/contents/year/2021/number/6/article/green-hydrogen-in-europe-do-strategies-meet-expectations.html>

³⁹<https://fuelcellworks.com/news/namibia-announces-9-4-billion-green-hydrogen-project/>

Meanwhile, countries like Kenya, Nigeria, and Morocco are at various stages of developing plans to integrate green hydrogen into their energy mix for the mid and long-term. In addition, at COP26 held in Glasgow, the United Nations pledged to support South Africa's Just Energy Transition with about 8.5 USD billion to develop upcoming economic opportunities in green hydrogen and a 17.8 USD billion plan to support a pipeline of green hydrogen (Yohannes & Diedou, 2022).

According to the International Renewable Energy Agency (IRENA) report on the Nigeria Renewable Energy Road Map. The report revealed that the potential of renewable energy will not only help to meet Nigeria's large energy deficits but also power sustainable economic growth and create jobs while achieving global climate and sustainable development objectives (IRENA, 2023). In this assessed renewable potential, green hydrogen is emerging as a frontrunner for achieving a clean, secure, just and affordable energy future not only for Africa and Nigeria, this will create exciting economic opportunities for the Nigerian economy (Africa's Green Hydrogen Potential, 2022). With abundant wind and solar potential, many parts of Nigeria are ideally positioned for green hydrogen production to build their energy independence and industrialization, while also meeting rising National energy demand.

Recently, the Nigerian Government launched its roadmap to carbon neutrality by 2060 and an estimated sum of \$1.9 Trillion is required (NETP, 2022). As part of its decarbonization strategy of the country's net zero targets, it has made plans to include about 9 GW and 34 GW by 2040 and 2050, respectively, in its power mix. Also, 4 GW and 22 GW capacities for hydrogen electrolyzer storage by 2040 and 2050. Also, the electricity demand of about 1 TWh and 46 TWh is projected to be met by electricity generated from electrolytic hydrogen in 2040 and 2050, respectively (NETP, 2022).

4.3. Methodology

This section presents the methodology to explore a low-carbon strategy for a typical developing country that explores carbon neutrality in a set timeframe. An open-source energy modelling tool is applied to the Nigerian energy system with a focus on the role of renewable energy towards a transition to net-zero emissions targets and developing a carbon-neutral strategy. In this case, the open energy modelling framework (oemof) is employed to investigate the role of green hydrogen as a future energy carrier in the Nigerian power sector toward its net-zero energy transition plan under different electrification pathways and policy constraints. The chosen optimization modelling

approach synthesizes and reflects in-depth insights not only on how the electric energy demand of i) existing; ii) suppressed and ii) non-electrified people can be met but also explores the strategic role of renewable hydrogen on Nigeria's net-zero emissions target. To do this, six scenarios have been defined based on governmental intended energy transition plans (Current Policy Scenarios) net-zero emission scenarios with energy efficiency (Best Policy Scenarios), and the role of green hydrogen on distributed electricity generation among the electricity Distribution Companies (DisCOs) in Nigeria is investigated.

4.3.1. The OEMOF framework and its building block

Oemof is an energy system modeling platform database integrated with Python (pandas) libraries, based on a modular open-source framework (Oemof-Team, 2020). Through collaborative development in an academic context based on open processes, oemof was developed to support a maximum level of participation, transparency, and open science principles in energy system modelling (Hilpert *et al.*, 2018). Thus, enhancing a prominent level of scientific standards (transparency, repeatability, reproducibility, and scrutiny) became pertinent to the overall system model framework. The oemof framework is based on a generic graph-based description of energy systems (Oemof-Team, 2020). It is differentiated into several dichotomies of energy system models each specified for a certain task in the energy system modelling process, of which, oemof-solph is one of its significant parts (Kaldemeyer, *et al.*, 2017).

Oemof-solph or solph is part oemof a meta-package, which has been developed to serve as an integrated energy system model (Krien *et al.*, 2020b). It generates energy system simulation and optimization models which are designed to solve and solve linear problems (LP) or mixed-integer linear optimization problems (MILP) from a generic object-oriented structure based on graph theory (Krien *et al.*, 2020a). Oemof-solph is built on the Python optimization model language (pyomo). Pyomo is an open-source modelling tool which provides classes and functions designed to create optimization functions via an Application Programming Interface (API) (William *et al.*, 2019). It enhances its functionalities to simulate or optimize multi-regional energy systems considering power, heat, and mobility. Its structure enables us to generate models on various levels of details employing predefined components and other possible additional expressions and constraints formulation, also, it is possible to switch between a dispatch and an investment model (Hilpert, *et al.*, 2017).

Oemof-solph employs a modular and generic system approach⁴⁰. OEMOF includes components such as energy technology transformation. Other major constituents include i) generation systems such as cogeneration, natural gas plants, solar arrays and wind turbines, diesel generators, etc.; ii) Transporting energy which consists of an electricity grid network; iii) electricity consumer/demand types – residential, commercial, and industrial consumers; iv) fuel such as gas and oil or hydrogen; and v) export - excess electricity generation is distributed where possible.

To simplify the rigorous modelling efforts in oemof, oemof-B3 was introduced which was used as a sector-integrated energy system model of Brandenburg and Berlin, Germany. It represents many sectors: electricity, central and decentral heat, hydrogen, CO₂, and methane. It is a multi- node model, which means that several distinct regions are represented that are connected via transmission lines (Oemof-B3, 2023). The model is a perfect-foresight; cost-minimizing linear optimization model based on oemof-solph, oemof Tabular and oemoflex. (Oemof-B3, 2023). The oemof-B3 has been adopted to develop a regional integrated model that explores how power systems are modelled in a distributed-generated approach.

Graph theory also known as the bipartite graph is a mathematical study of graphs. Their mathematical structure models pairwise relationships between objects. An oemof graph is represented as a network of nodes and edges. A node can either be a bus or a component; the bus is a virtual element that connects different components of the energy system and must be balanced at every stage of the system. Also, a bus corresponds to a node or cell in the energy system. The edges represent the input and output of a component, they consist of flows, the flow is a very significant component of oemof because the edge is responsible for energy flow between two nodes and is often used to measure system costs. Figure 4.2a. shows a diagrammatic illustration of graph theory, comprising nodes, edges, bus, component, and flow. Figure 4.2b shows the basic representative use and flow of the oemof model.

The generic approach to modelling in OEMOF is divided into two levels: components and graphs. The components consist of a source, sink, and transformer. The source is explained as having one output with no input. It can be used to model energy sources such as solar and wind power plants, and coal or gas and oil power plants.

⁴⁰<https://oemof-solph.readthedocs.io/en/latest/reference/oemof.solph.components.html>

On the other hand, the sink has one input, no output, which is employed to model energy consumers, energy excess, or a reduction in energy consumption, while the transformer connects inflows to outflows through one or more conversion factors. In this regard, it can be used to simulate power plants such as Combined Heat and Power (CHP) Plants, or gas turbines that operate with a constant efficiency or capacity factor.

Other generic features provided by OEMOF include but are not limited to, power generation systems, electricity distribution costs, and pricing. While the components described are basic or generalized functions in oemof there are some experimental or other components, which include: ExtractionTurbineCHP (component), GenericCHP (component), GenericStorage (component), OffsetTransformer (component), ElectricalLine (experimental), GenericCAES (experimental), Link (experimental), SinkDSM (experimental) more information on description and codes are in the oemof-solph open documentation⁴¹.

⁴¹<https://oemof-solph.readthedocs.io/en/latest/>

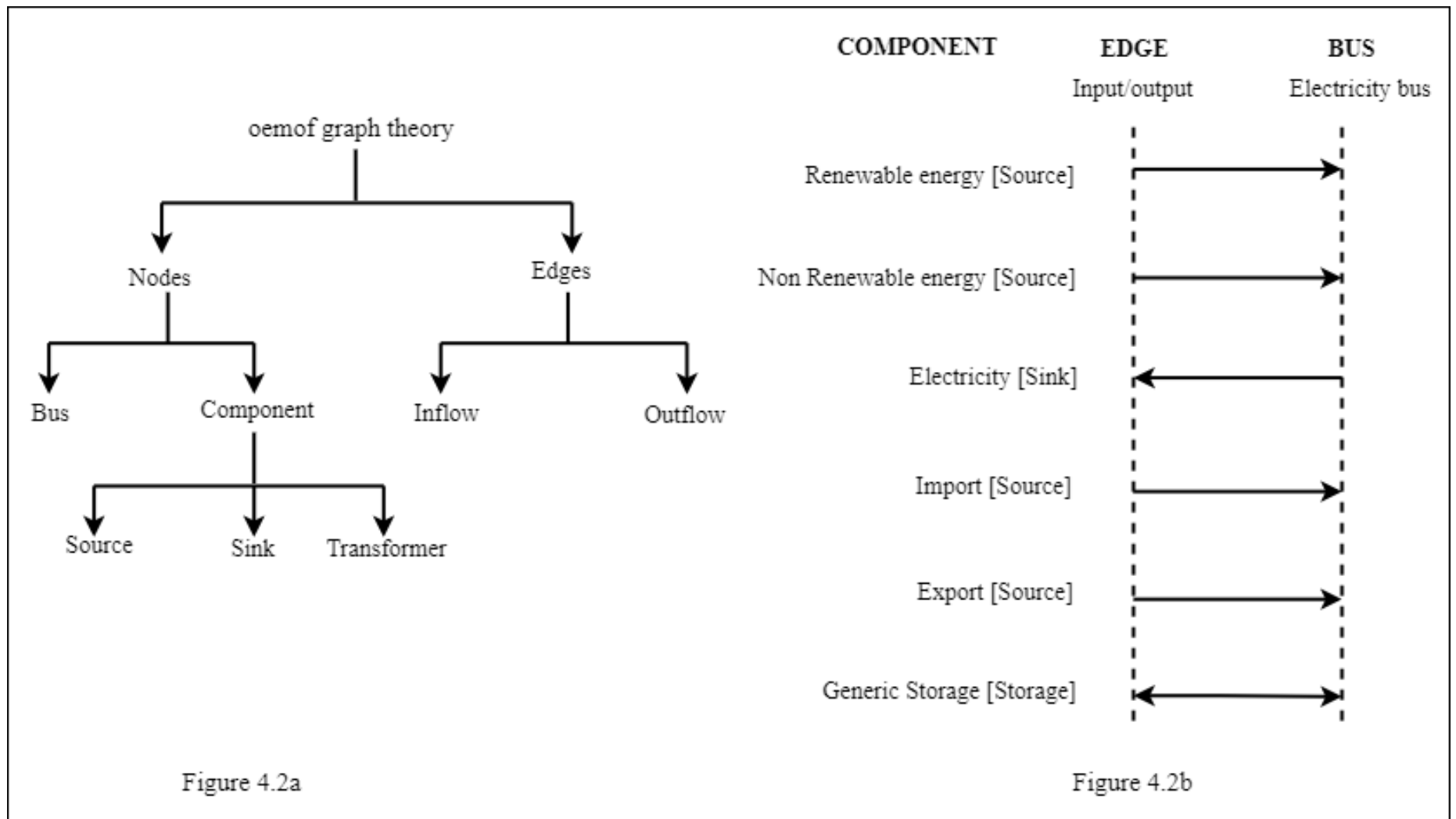


Figure 4. 2. (a) Diagrammatic illustration of the graph theory and (b) Basic representative flow of the oemof model.

While Figure 4.2 a, show a graphic theory as it is applied to an oemof framework and its virtual representation in b Figure 4.3 presents a schematic illustration of a simplified energy system in an oemof framework. Figure 4.3 further demonstrates how the oemof model framework can be employed to model a simplified energy system. Renewable and fossil fuel energy represents the energy source, the storage system represented here is a general storage scheme as it has not distinguished between different types of storage systems. As seen in the diagram the storage allows a dual energy flow, in that, electricity/current stored could be released when needed. Also, the figure has illustrated two types of sinks, the demand or energy consumers and excess energy that could be exported to other consumers.

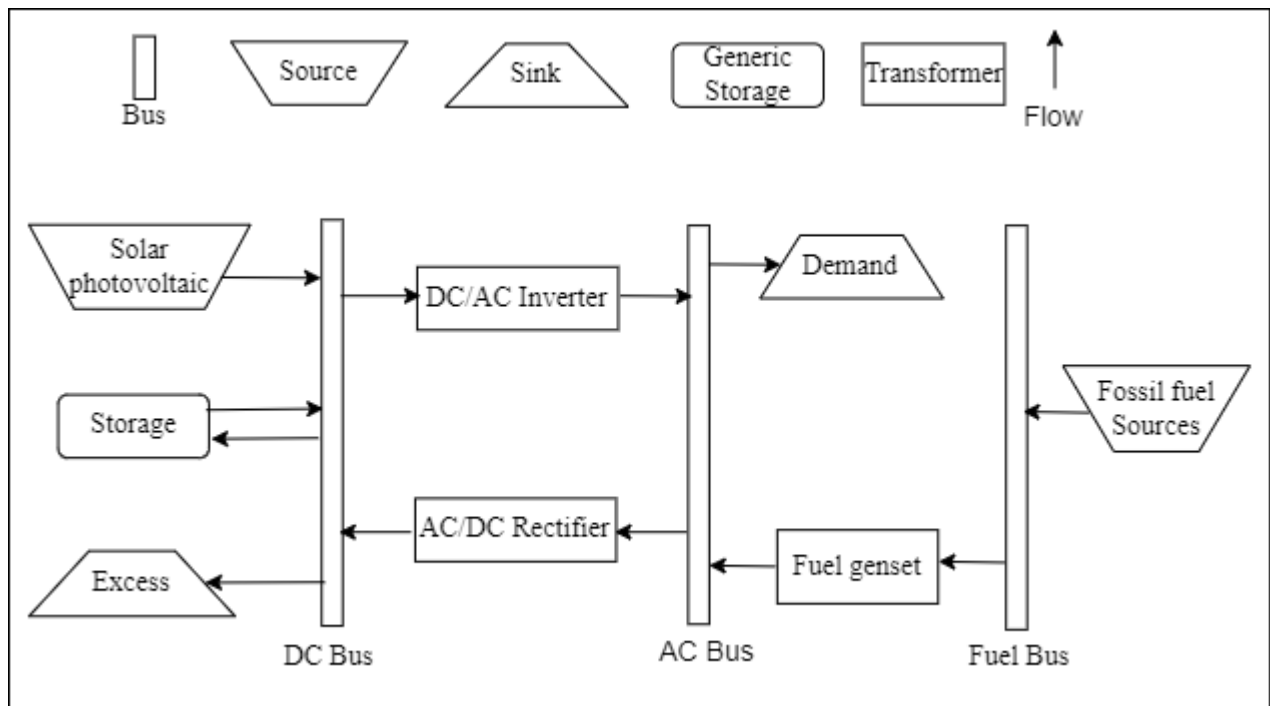


Figure 4. 3. Schematic illustration of a simplified energy system in oemof.

In addition, transformers are represented as inverters, rectifiers and fuel genset, this implies that energy sources such as solar or fossil sources could be transformed into useful energy. Examples of such transformers found in fuel generators are conventional diesel/petrol generator sets, and gas or oil power plants. The inverter converts direct current (DC) generated from renewable energy like solar panels to alternative current (AC) compatible with consumer appliances. Conversely, alternative electrical currents generated from non-renewable sources (through power plants) are converted into a direct current by using a rectifier. This electricity converted from AC to DC is to enable the current to be saved in batteries/storage devices for later usage.

4.3.2. System Analysis of Green Hydrogen Technology

The oemof-solph framework is adopted to explore the system analysis of green hydrogen technology in the Nigerian power sector, towards her carbon neutrality target. Figure 4.4 shows the reference energy system (RES) by which the oemof framework would adopt to model the Nigerian power sector through coupling hydrogen technology.

According to Figure 4.4, the far left represents primary energy sources which include gas, fuel oil, diesel, nuclear, biomass, wood fuel and geothermal. The energy sources are processed into useful energy – electricity - by the various power plants, however, renewable energy sources are also sources of electricity including electricity imports. To the far right suggest several uses and applications of electricity generated, which include electricity export, curtailment, storage and electrolyzer. The aim of the RES is for the electricity demand to be met as to is considered a power-to-gas (P2G) or a sector coupling arrangement, thus, a key form of power sector coupling.

The right side of Fig 4.4 represents the process of exporting, curtailing or storing excess electricity for late usage. Also, excess electrical energy is converted into storable chemical energy in batteries. More so, the excess electricity generated is used in a hydrogen electrolyzer, that is, the use of electricity to separate water into hydrogen gas and oxygen, although the process of electrolysis of water is more advanced than what is presented in Fig. 4.4. While the oxygen gas produced is let to disperse into the atmosphere the resulting hydrogen gas is stored and used when required or made to be recombined with oxygen gas in a fuel cell. To make the hydrogen gas produced from the electrolyzer useful, the fuel cell is used. The hydrogen fuel cell then converts the hydrogen into electricity which is then used to meet electrical demand.

Figure 4.5 shows a clearer model of green hydrogen production in Nigeria. Here, the oemof conventional symbols have been used to represent how hydrogen can be generated from excess electricity obtained from renewable energy sources

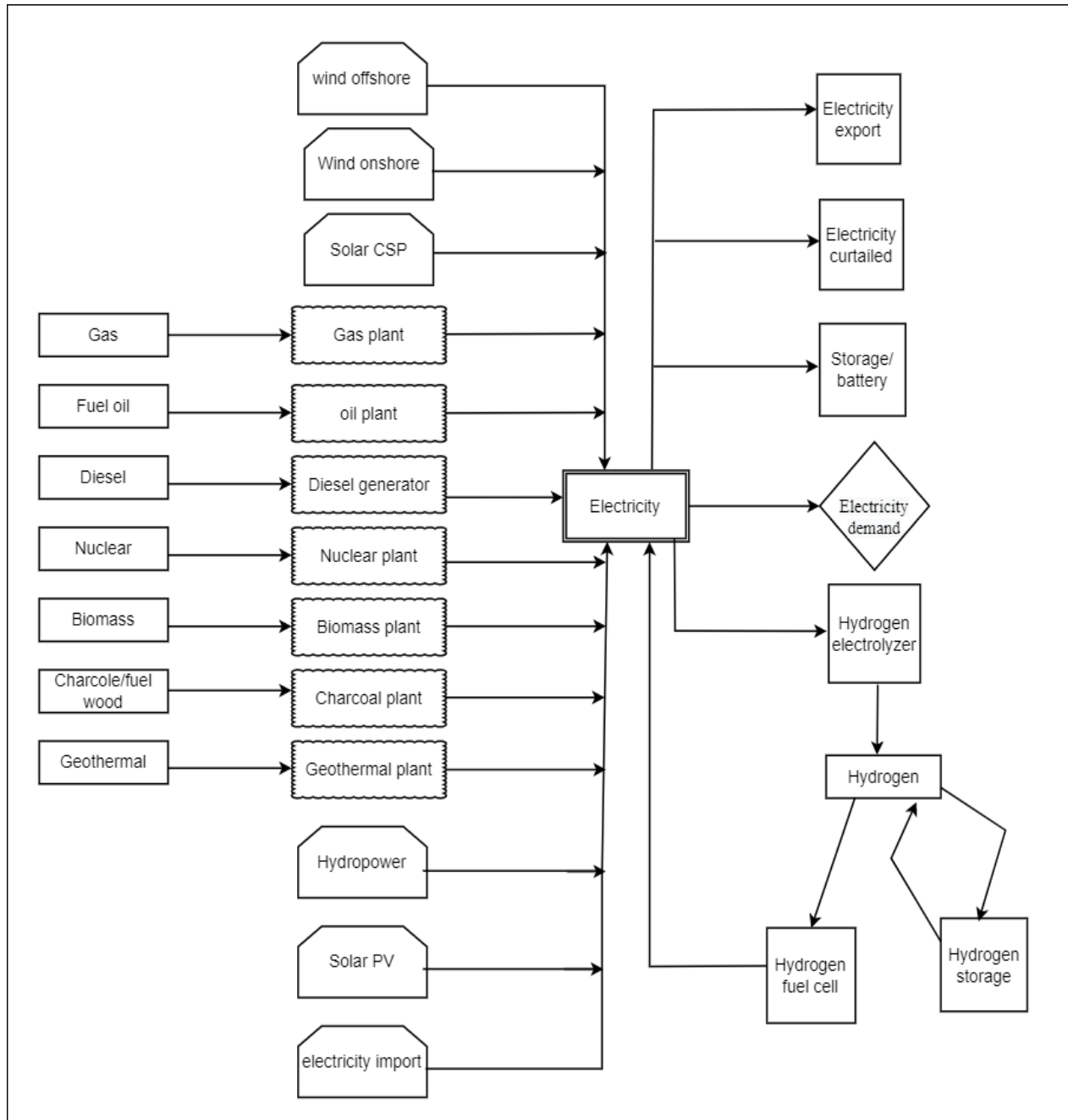


Figure 4. 4. The reference energy framework for the power sector coupling.

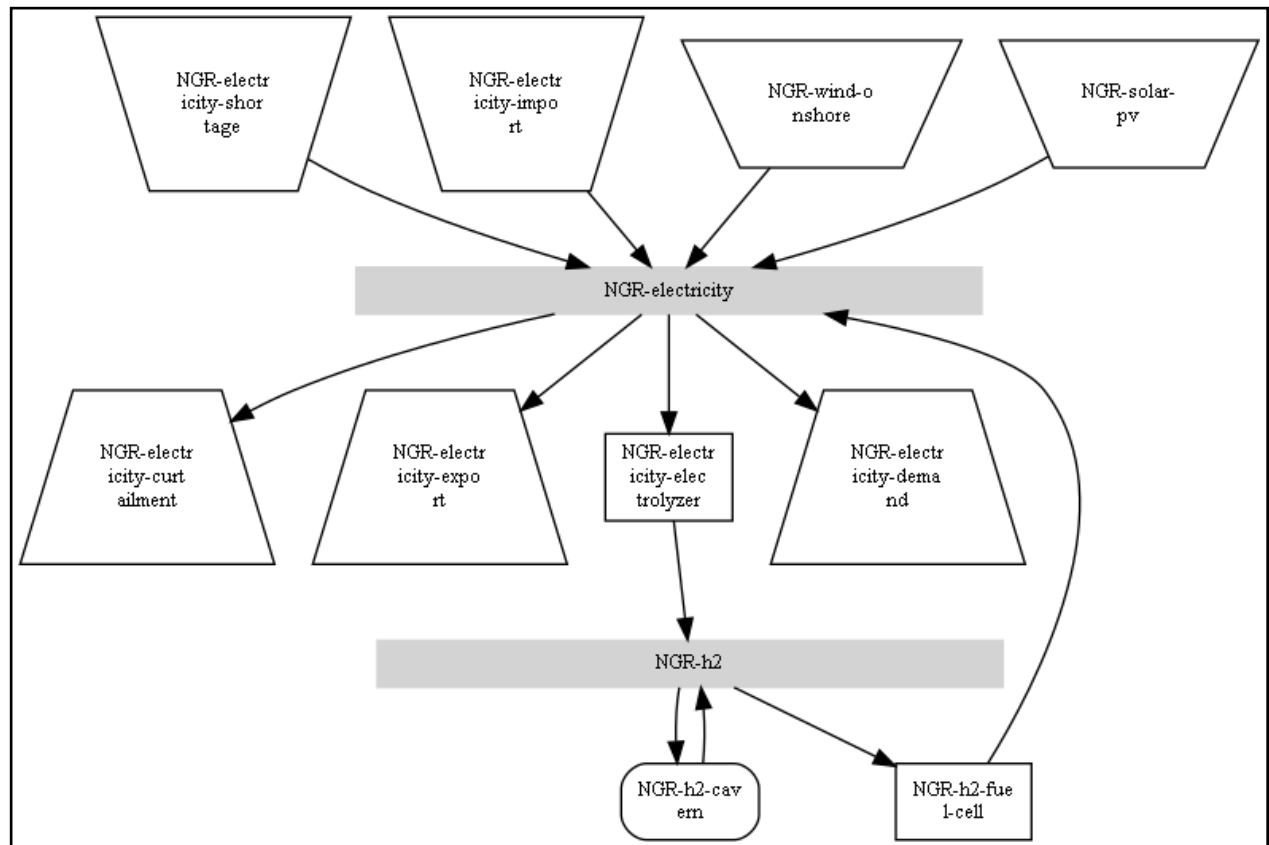


Figure 4. 5. A simplified oemof model output for green hydrogen.

4.3.3. Model Scenarios

To investigate the study research questions and scenarios are developed. Table 4.1 describes scenarios that are aimed at meeting energy demand or suppressed demand and non-electrified demand. The Nigerian load curve used to estimate hourly electricity demand was retrieved from Toktarova *et al.* (2019) and improved upon to fit the scope of the scenarios. The outcome was then used to as a benchmark to model the development scenarios that explore how to achieve net-zero emissions targets while meeting demand. It is important to reiterate that scenarios assumptions are guided from the analysis of the stakeholders' perspectives presented in chapter one.

Three scenarios are presented in Table 4.1 that is, the business as usual (BAU), the sustainable scenario, and the carbon neutral scenario. The BAU scenario describes the current energy situation and the current energy growth in Nigeria. It assumes the energy status quo across the 2030, 2040 and 2060 modelling periods. Each model period details the input assumptions. The 2030 model period assumes gradual investment in solar energy for off-grid according to the Rural Electrification Agency (REA) report (REA, 2016) while the 2045 and 2060 model period assumes

that natural gas as a transition fuel with decreased captive diesel generators and also, a significant investment in solar technology as a reduction in diesel usage, respectively.

The sustainable scenario describes a rigorous investment in renewable energy targets both for off-grid and on-grid, solar home systems for prosumers and energy efficiency on the demand side while reducing usage of diesel/petrol use and improving the adoption of gas usage as a transition fuel. The scenario assumes an investment in energy efficiency renewable energy (RE) resources at 30% following the NDC, (2021) in 2030, while more investment in RE and EE according to conditional NDC by considering a deliberate fuel-switching effort and banning the use of diesel/petrol generator by 2045 and 2060, respectively.

The third scenario is referred to as the carbon-neutral scenario. Here, the scenario aims to achieve net zero emissions by investing in Nuclear, bioenergy, hydrogen and fuel cells are considered beyond the sustainable scenario. To do this, the scenario assumes implementing the net zero plan according to NETP (2022), including a gradual investment in Nuclear, bioenergy and hydrogen fuel cells, more so, considering a significant investment in solar energy for green hydrogen for export in the model period, respectively. Scenarios are summarized in Table 4.1. More so, the scenario description presented in the same Table (Table 4.1) assumes an electricity demand increase that is based on the Gross Domestic Product growth rate in Nigeria.

The GDP growth rate assumptions are based on the World Bank report and the analysis from the Energy Commission of Nigeria (ECN) presented in (Sambo, 2008; Precious Akanonu, 2019). The scenario assumes that electricity demand would increase at a GDP growth rate of 8% in the BAU, 11% and 13% in the sustainable and carbon neutral, respectively. However, the assumption would be relevantly applied in the model period 2045 and 2060 in the scenario.

Table 4. 1. Scenario development and description of net zero emissions target.

Scenario	Description	Assumption
Business as usual (BAU)	This considers the current energy situation from 2020. Considers current status quo and energy growth rate in renewable energy (RE) on-grid/off-grid and prosumers for underserved areas	2030 – gradual investment. in decentralization
		2045 – gas as a transition fuel with decreased captive diesel generators
		2060 – a significant investment in solar technology reduction in diesel and at an increased demand of based on 8% GDP growth rate
Sustainable	This considers rigorous investment in RE – on-grid/off-grid and prosumers and energy efficiency on the demand side, while reducing diesel gen use above BAU, improved gas. Model values adopted from the current NETP and NDC (NETP, 2022).	2030 – RE grows by 30% and investment in EE according to NDC
		2045 – more investment in RE and EE according to conditional NDC
		2060 - Outlaw the use of diesel generators and an increased demand based on 11% GDP growth rate
Carbon Neutral	To achieve Net zero with investment in Nuclear, bioenergy, hydrogen and fuel cells are considered beyond the sustainable scenario.	2030 – net zero plan
		2045 – gradual investment in Nuclear and hydrogen fuel cell
		2060 – an increased demand based on a 13% GDP growth rate and with significant investment in solar for green hydrogen

Table 4.2 presents the scenario that explores a distributed generation strategy from the five DisCos. It comprises two scenarios based on a regional model for a model period of 2030 and 2060.

According to scenarios presented in Table 4.2 comprising of regional model 2030 and regional model 2060. The regional model 2030 describes the gradual fading out of the use of diesel generators and investment in alternative green technologies, while the second scenario illustrates the replacement of fossil fuel sources with clean alternatives, especially green hydrogen and fuel.

Table 4. 2. Scenario for distributed energy system planning.

Scenario	Description
Regional model 2030	Take into account the gradual fading out of diesel generators and investment in alternate green energy technology
Regional model 2060	Assumes the replacement of fossil fuel sources with clean alternatives, especially green hydrogen and fuel

Additionally, the carbon neutral scenario was subjected to further analysis to reflect a distributed generation strategy (This is represented in Table 4.2). This was done as an aggregated model to explore the role of green hydrogen in the Nigerian power sector via the Electricity Distribution companies (DisCos). The DisCos considered are based on the availability of renewable energy resources availability especially solar and wind according to Ohunakin, (2010). Relevant DisCos that fit the renewable energy resources reported by Ohuakin, (2010) domicile in the Northern part of Nigeria (shown in Fig. 4.6), include i) Kaduna electricity distribution company; ii) Yola electricity distribution; iii) Abuja electricity distribution iv) kano electricity distribution; and v) Jos electricity distribution. The DisCos jurisdiction covers nineteen states out of thirty-six states in Nigeria.

Figure 4.6 shows the five electricity distribution companies considered in the study. They include i) Kaduna distribution company comprising four states that are, Kaduna, Zanfara, Kebbi and Sokoto; ii) kano distribution company with three states namely Kano, Jogawa and Kastina; ii) Yola distribution company consisting of four states namely Yobe, Borno, Adamawa and Taraba state; iv) Jos distribution company comprising of four states namely Bauchi, Gombe, Plateau and Benue state; and v) Abuja distribution company consisting of Niger state, Federal Capital Territory (FCT), Kogi and Nassarawa.

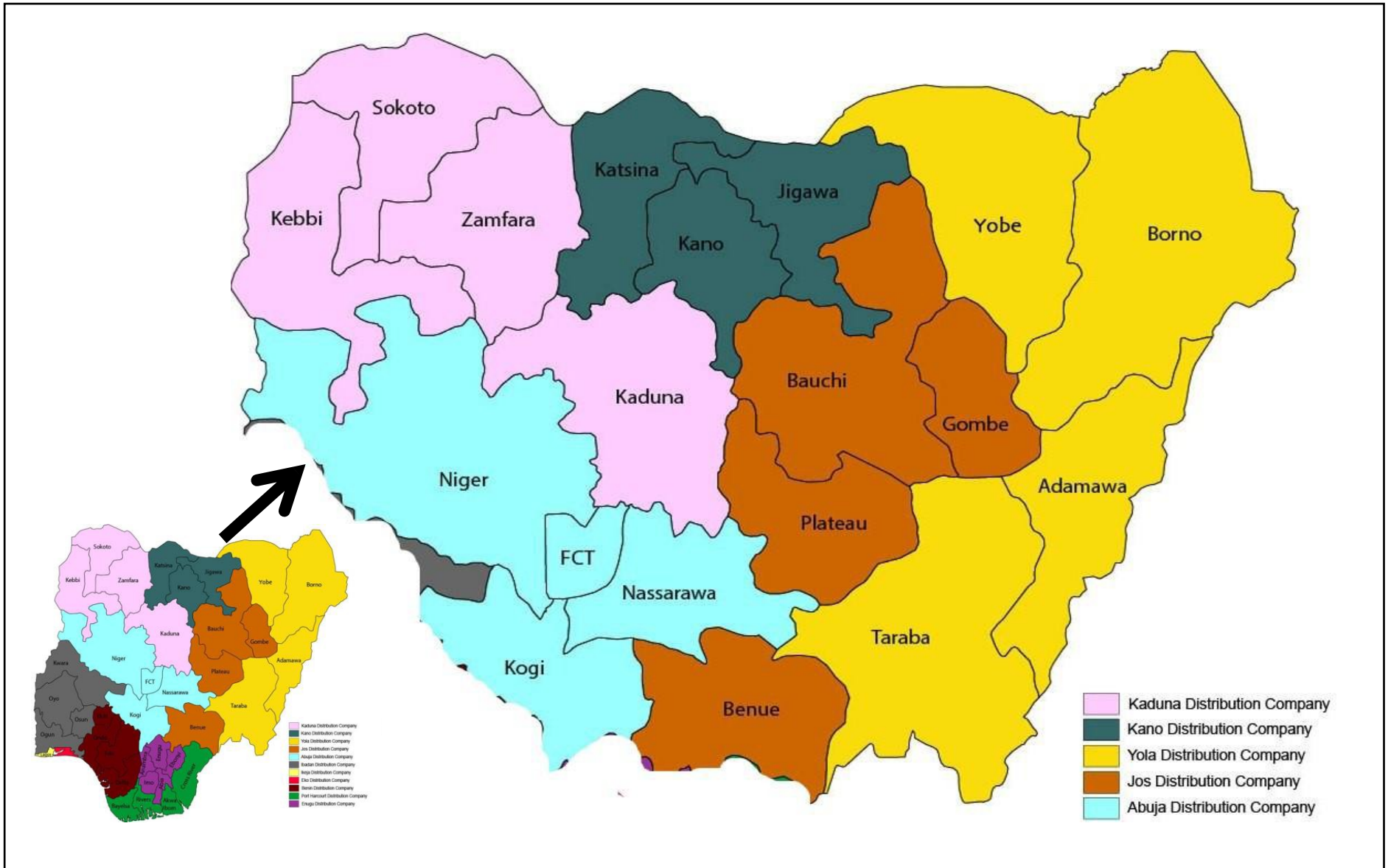


Figure 4. 6. The five distribution companies DisCos (Source: NERC).

4.4. Results and Discussion

Results from the scenario models are presented in this section. To begin with, models were developed based on the oemof framework and validated by developing a business-as-usual model as shown in Figure 4.7. The Nigerian electricity demand profile utilized for the study was adopted from Toktarova *et al.* (2019) and then used to benchmark the model (Toktarova *et al.*, 2019). An hourly dispatched model which shows the current power situation in Nigeria is used to validate the model, as shown in Figure 4.7.

The result from the model validation shown in Figure 4.7 revealed the heavy use of diesel/petrol-powered generator fuel in the country representing over 60% of total electricity generated in 2020. This means around 19 GW of power demanded in that year including off-grid and on-grid were met by captive diesel/petrol generator sets. Current validation proof follows and is in line with media reports and the World Bank survey (World Bank, 2014; Nnodim, 2022). Also, Figure 4.7 shows that less than about 30% of the national power demanded was met by on-grid tired gas and hydropower plants, combined, while about 20% of electricity demanded were never met, these are the unmet electricity demand, while those met from captive diesel/petrol generator sets are regarded as suppressed demand.

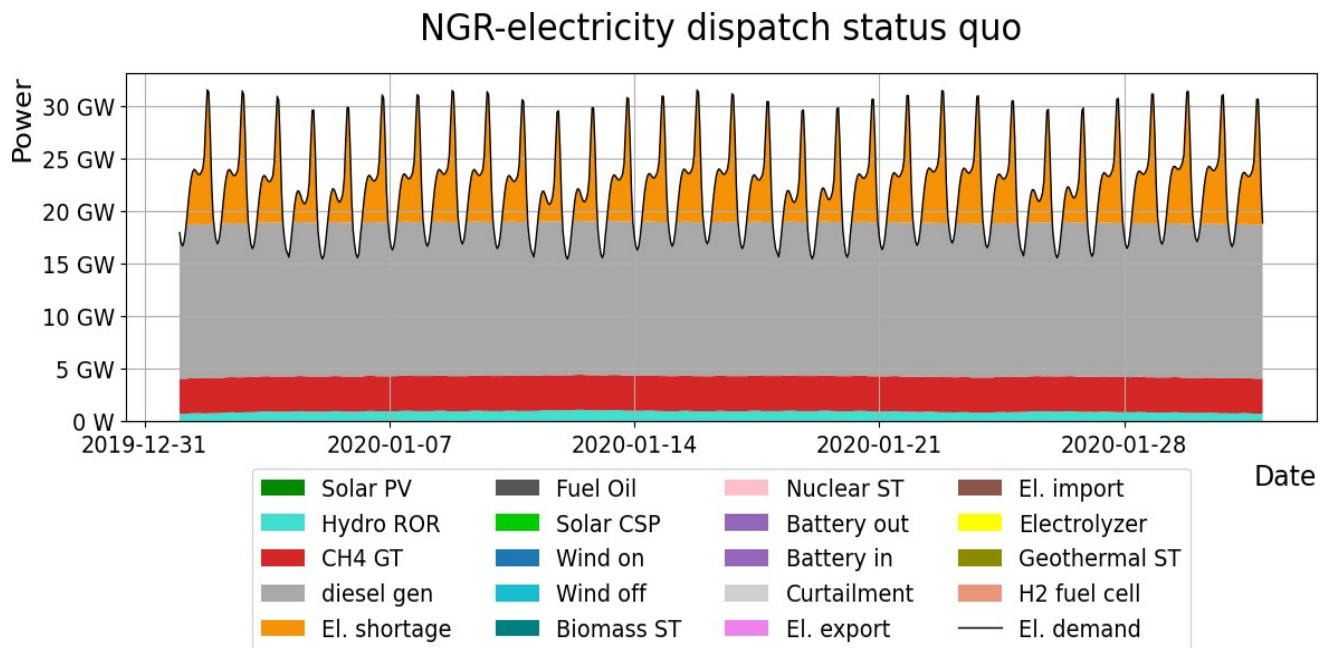


Figure 4. 7. Model validation via power dispatch ~ current power situation indicating heavy use of diesel generator, high suppressed and unmet demand.

4.4.1. Discussion of the result based on Table 4.1 - Net-zero emission strategy

Figure 4.8 shows the capacity evolution of the business-as-usual scenario across the model period. Exploring the clean energy strategy in the BAU scenario towards a net-zero emissions agenda, Fig. 4.8 revealed that diesel/petrol-fueled generators will still serve as the main supply of power in Nigeria by 2030. The same figure also revealed that there would be about a 40% reduction in the usage of diesel-fueled generators by 2045 and there will be no significant usage of captive diesel/petrol generators by 2060. In the same scenario, natural gas is a significant part of the energy mix in 2030 and 2045, however, about a 29% reduction in natural gas in the mix by 2060.

Renewable energy especially solar photovoltaics (including solar mini-grids and solar home systems) has experienced significant growth from 2030 up until 2060 representing the largest single energy source in the business-as-usual scenario. Hydrogen and fuel cells have gained low acceptance in the energy mix, with a constantly low growth rate from 2030 to 2045 but experienced a relatively increased growth rate by 2060. Hydropower has seen significant growth of about a 50% increase in the BAU scenario. For bioenergy, a sharp rise was experienced from 2030 to 2045, but this became constant by 2060. Due to the increased contribution of renewable energy in the scenario electricity storage in battery has been employed and has experienced significant growth from 2045 to 2060.

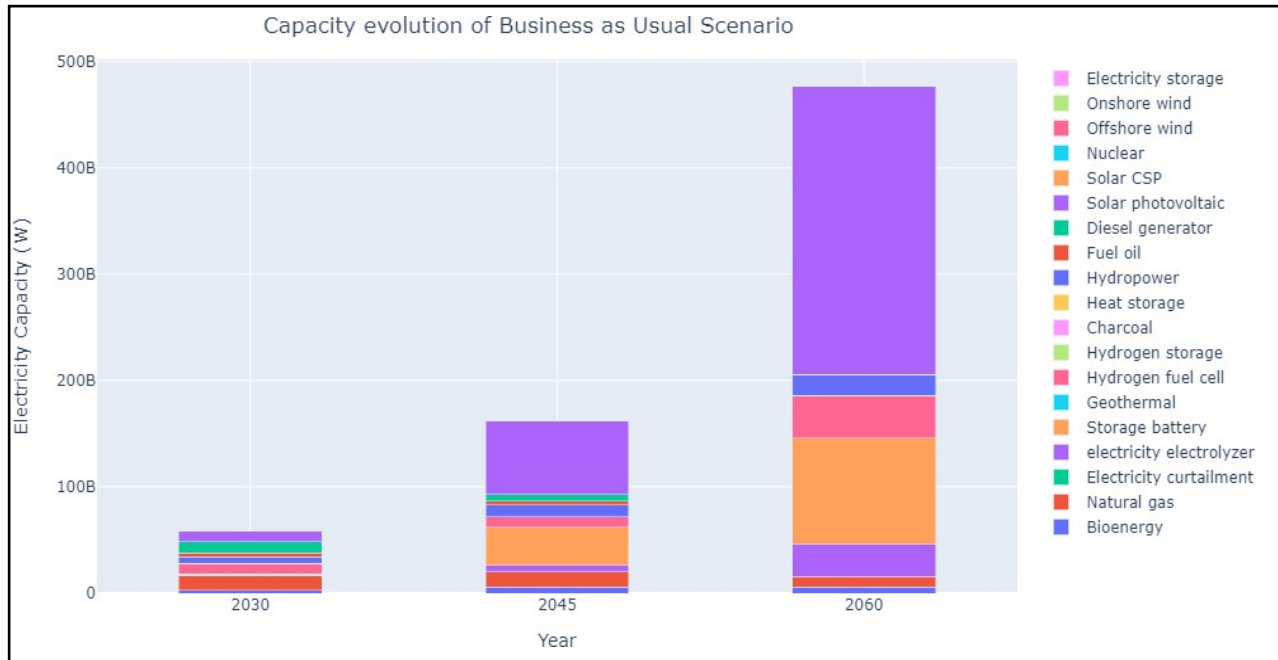


Figure 4. 8. Evolution of Business-as-Usual scenario across the model periods.

The scenario has identified that there will be a need for a significantly high level of investment in the power sector moving forward from the base year (i.e., 2020) to achieve such a mix. While the scenario has shown a significant increase in the share of renewable energy in the energy mix this suggests that an over significantly large share of solar photovoltaic might not be sustainable due to the large share of storage required with increased cost. Despite the share of the renewable energy mix and the inclusion of hydrogen and fuel cells the scenario still employs some level of electricity supplied by diesel generators. These imply that the BAU scenario is not enough of a mix that would eradicate the use of captive diesel/petrol-fueled generator sets and may not deliver the needed carbon neutrality expected not even in the long term.

The sustainability scenario presented in Figure 4.9 shows the evolution of the energy technology mix over the 2030, 2045 and 2060 model period. In the sustainability scenario, the evolution of fuel oil used in diesel power plants was observed to be marginal in 2030 when compared to the BAU scenario. While natural gas was seen to have met about 20% of energy demand in 2030, power from diesel generators accounted for about 16% of the overall production that year, thus a reduction to the BAU. In terms of renewable energy share, investment in solar energy was prioritized in 2030, however, this includes both on-grid and off-grid systems about 20% of electricity was met from solar sources (NB. Solar sources have been aggregated to include all

solar sources). More so, onshore wind and bioenergy sources account for about 5% of each of the mix, while hydropower assumes about 8% of the total mix. Overall, in 2030, the sustainability scenario shows almost an equal mix of both renewable energy and fossil fuel energy sources.

Subsequently, in 2045, the sustainability scenario increased the share of power generation due to increased demand in that modeling period. In this modeling period, the share of Fossil fuel sources was marginal accounting for about 6% of energy generation by source. While renewable energy sources accounted for about 56% with solar accounting for over 80% of the renewable energy share. Also, generation from hydrogen in terms of its fuel cell accounted for about 7% of total generation, while storage in terms of battery storage and electricity storage from hydrogen accounted for around 25%. This is likely due to the high share invested in renewable energy, thus balancing its unstable nature. This modeling period has shown the significance of fuel switching from heavily dependent fossil fuel sources to a wide mix of energy sources.

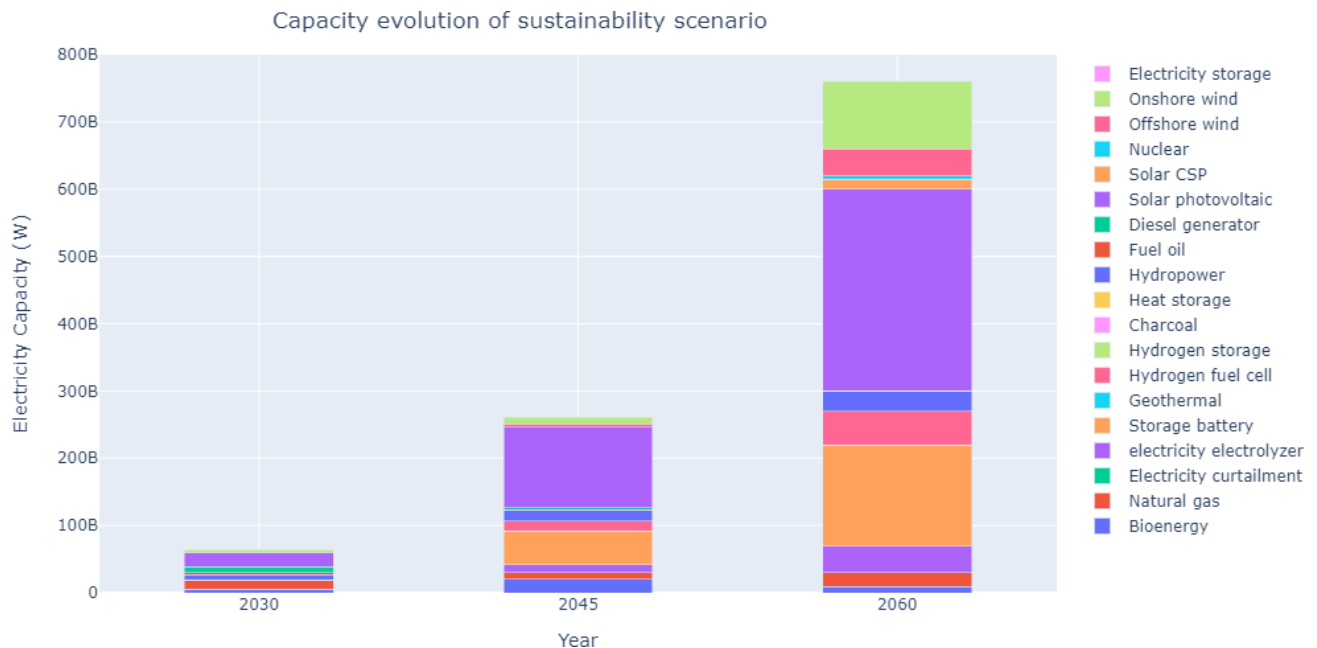


Figure 4. 9. Evolution of Sustainability scenario across the modeling period.

Successively, in the modelling period of 2060 in Fig.4.9 there is no use of a captive diesel generator, although, the only fossil fuel source is from gas which accounted for about 2.5% of the total energy mix. Electricity generation from renewable energy sources is highly significant accounting for about 65% of total electricity generated, while the share of solar PV represents around 62% of total renewable energy sources. Generation from hydrogen fuel cells accounted

for around 6.6%, while electricity storage and battery storage accounted for about 25% of the total electricity supplied.

In the carbon neutral scenario represented in Figure 4.10. The 2030 modeling period suggests a substantial energy mix, however, there is evidence of a captive generator set used for electricity generation in the mix. No trace of a diesel generator was observed in the modeling period in the scenario. Although, natural gas was seen as a fossil fuel source across the modeling period. The 2045 model year has shown a similar energy mix to that obtained from another scenario in the same model year; however, the availability of nuclear sources is distinct. And the 2060 model year of the same scenario in Fig. 4.10 solar, hydrogen and storage are prioritized in the mix, although the scenario had more electricity demand.

Discrepancies in the electricity demand across the modeling period are part of the model assumptions that electricity demand would increase in 2050 -2060 based on the GDP growth rate according to the World Bank and Energy Commission of Nigeria reports. The carbon-neutral scenario is designed for the highest energy demand.

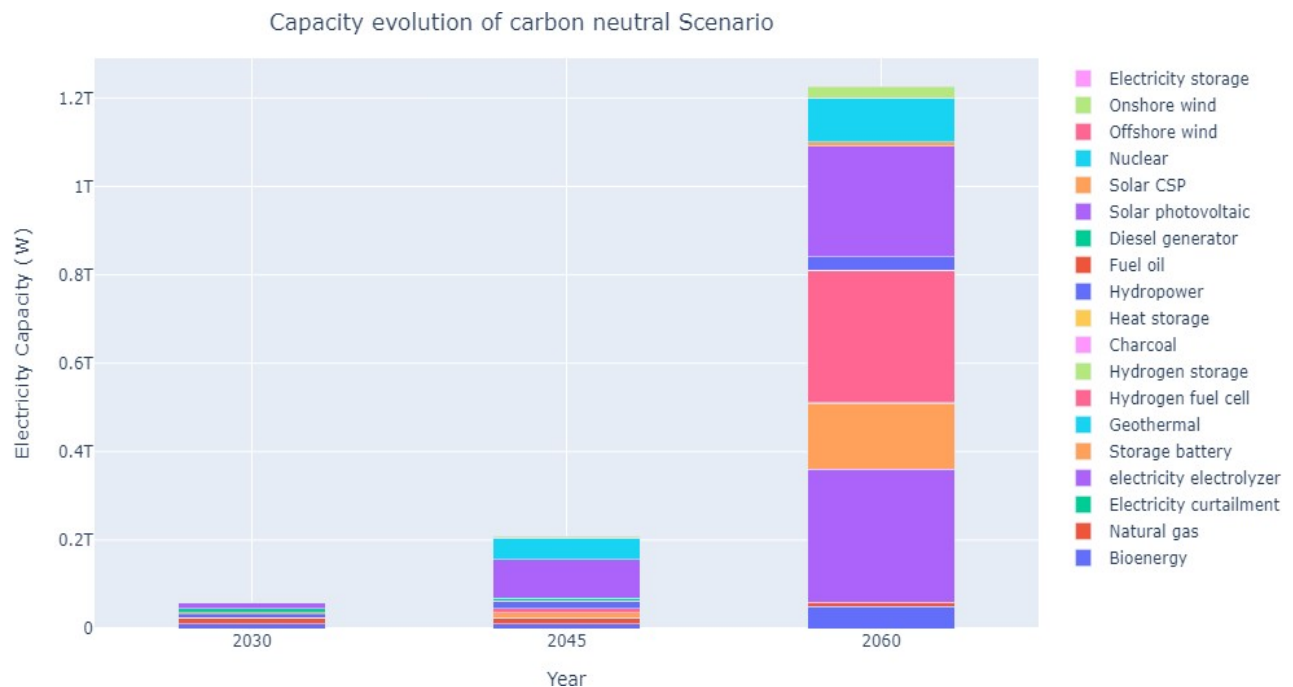


Figure 4. 10. Evolution of Carbon neutral scenario across the modeling period.

4.4.2. Discussion of the result based on distributed generation via DisCos (Scenario Table 4.2)

Figure 4.11 shows the hourly dispatched electricity generation capacity in the modeling year 2030 in the Nigerian power sector. The result from the model is simplified to show generation and distribution flexibilities and reflect hourly variabilities in electricity generation from renewable energy sources, such as wind and solar. The month of January has been considered to reflect the aforementioned concerns in the generation, and power distribution among the DisCos. More so, as earlier explained five DisCos have been selected among the eleven DisCos because the five DisCos have higher solar and wind resources compared to other regions except for the region located along the seashore with higher wind resources such as EKO and IKEJA distribution companies. Also, this would help manage computation times as simulation could fail with many connections. It is important to note that the demand represented aggregate both on- grid and off-grid power demand.

The ABJ-electricity dispatch represents the Abuja electricity distribution company showing a total demand of about 5.5 GW of power. The ABJ DisCos shows how power demands are met by considering the energy mix. The ABJ DisCos shows that solar and wind have high variability due to their seasonal and hourly availability, while capacity from hydropower and Natural gas serves as the base load to cater for the observed variability in the system. It shows no signs of electricity curtailment of storage, this could be due to the high demand with relatively insufficient capacity. However, the suppressed demand was catered for by the use of captive diesel/petrol generators. This implies that by 2030 diesel generators will still be dispatched to the Federal Capital Territory (FCT) to make up for the unmet demand.

The JOS-electricity dispatch represents the JOS electricity distribution company; it supplies states shown in Figure 4.11. Similar generation is observed as that observed in the Abuja DisCos, although, more variabilities in the solar PV and little natural gas deployed to the distribution network. Larger suppressed demand thus, unmet demand is noticed which is expected to be met from diesel/petrol generators. No curtailment of electricity.

More so, the Kaduna electricity distribution company represented as KAD-electricity dispatch shows a similar generation trend but more hydropower dispatched. However, solar and wind generation are observed but not supplied as base load. Although other sources of capacity may have been generated marginally this will be explained better in Figure 3.19. while the Kano distribution

company dispatched more natural gas, with little renewable energy and evidence of power import. This has revealed that electricity has been transmitted from other distribution companies to meet some power demand. However, there are still some unmet demands, which are suppressed

The Yola distribution company shows some differences compared to the other distribution companies in that hydropower was the major supply with supply from solar. It revealed from Yola DisCos that some electricity was stored and some transmitted to other DisCos such as the Kano DisCos as shown in Fig. 4.11. However, Figure 4.11 might not give the full scope generation across the whole scenario. Figure 4.12 will therefore make up for this by revealing the capacities across the DisCos.

Consequently, Figure 4.12 shows the aggregated capacity according to the distribution companies. It revealed that the Abuja and Yola DisCos have the largest capacity and this is because of the highest energy demand in that region. Figure 4.12 presents the clear overall outlook of capacities that have been dispatched in Fig. 4.11, it shows that natural gas will be the main fuel by 2030 followed by solar energy resources, this could be due to the current investment made to electrify its rural and underserved areas with energy from the sun – solar PV in the form of mini-grid systems and solar home systems. While among other renewable energy sources wind and hydropower are planned to be effectively deployed. More so, diesel generator shows a significant source of capacity come 2030 while biomass transformed into bioenergy is likely to be among the mix by 2030.

Figure 4.13 shows hourly electricity dispatched for five electricity distribution companies for January 2060. It is interesting to know that all distribution companies show similar characteristics, although with an increase in electricity demand and thus an increase in generation from solar PV. Interestingly, no diesel/petrol-fuelled generator was dispatched to the system. The figure shows that all suppressed demand has been met through adequate transmissions among the DisCos. excess electricity was curtailed and exported to other DisCos regions. Excess electricity generated from renewable energy has been stored and utilized through electrolysis to produce green hydrogen from fuel cells. The fossil fuel source, especially natural gas is marginal. The Kano distribution company does not show the likelihood of dispatching hydropower, but still, electricity demand is met.

In addition, Figure 4.13 reveals the outcome for the second scenario described in Table 4.1, the regional model 2060. It assumes the full replacement of all fossil fuel sources with clean alternatives while green hydrogen takes prominence. Results from the current scenario imply that electricity distributed transmission will play a significant role in meeting unmet/suppressed

demand in Nigeria in the future say 2060. This means that power will have to shift from the current centralized scheme and would be generated on a regional basis, based on existing jurisdiction already supplied by the DisCos.

While electricity demand is met across all the DisCos, supply from natural gas still serves as the base load, this may be due to the rigorous effort the country has put into natural gas as a transition fuel, which will stay in the country's power mix for a long time. It is also important to note that the electricity dispatched represented in Figure 4.13 does not show full variabilities across the whole year but has simplified this to focus on the beginning of the year – January as this would provide more clarity and a glimpse of how the system behaves. To present the full system power capacity Figure 4.14, therefore, shows an aggregated capacity for the five DisCos.

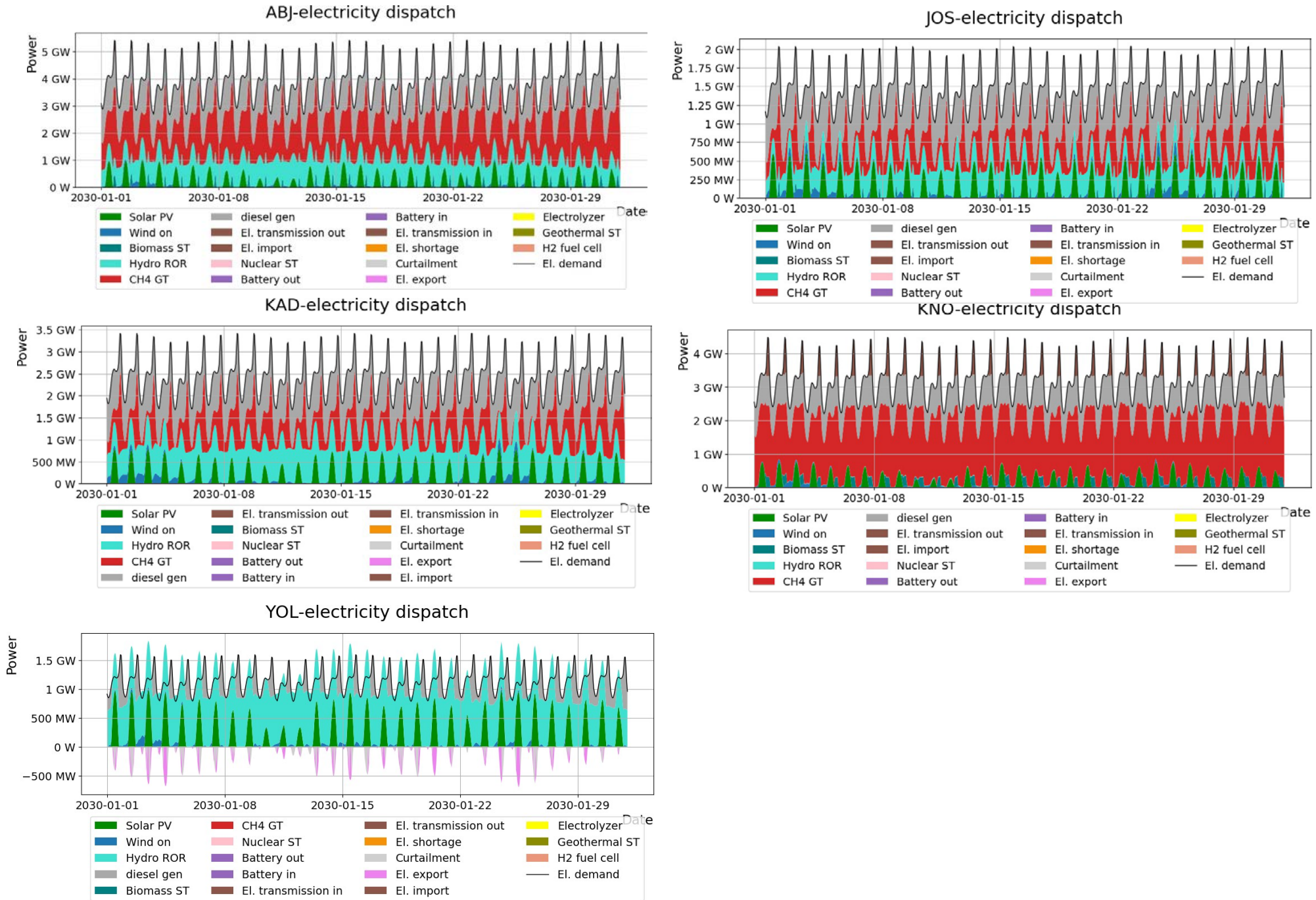


Figure 4. 11. Hourly electricity dispatched for five DisCos in the Nigeria Power Industry for the month of January, 2030.

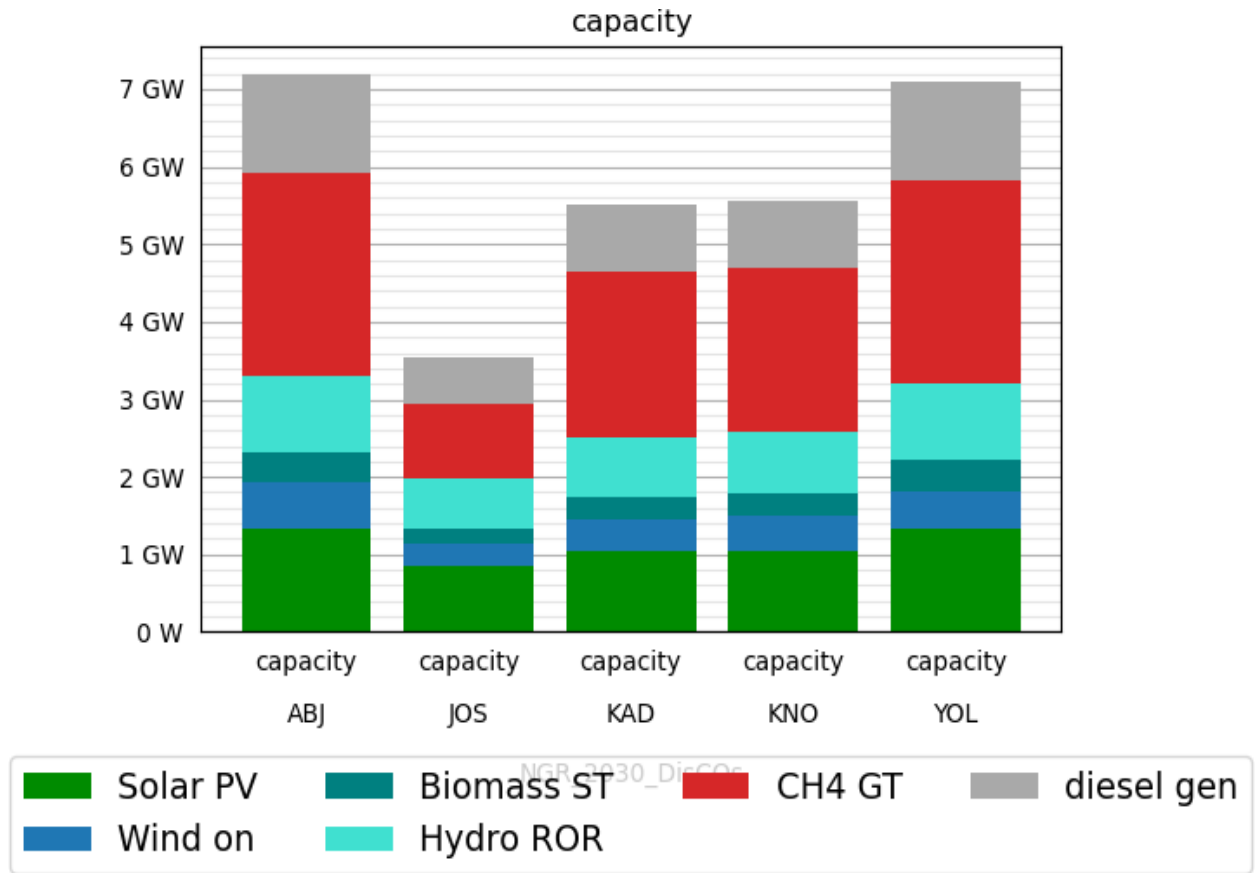
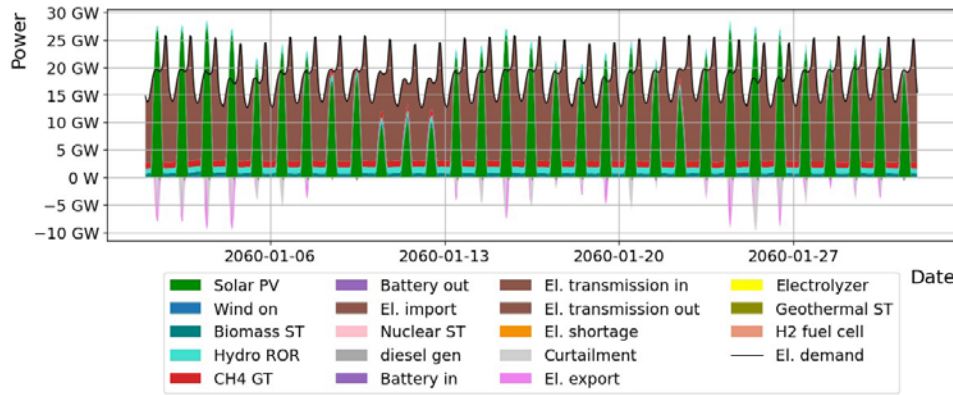


Figure 4. 12. Aggregated capacity across the Distribution Company by 2030.

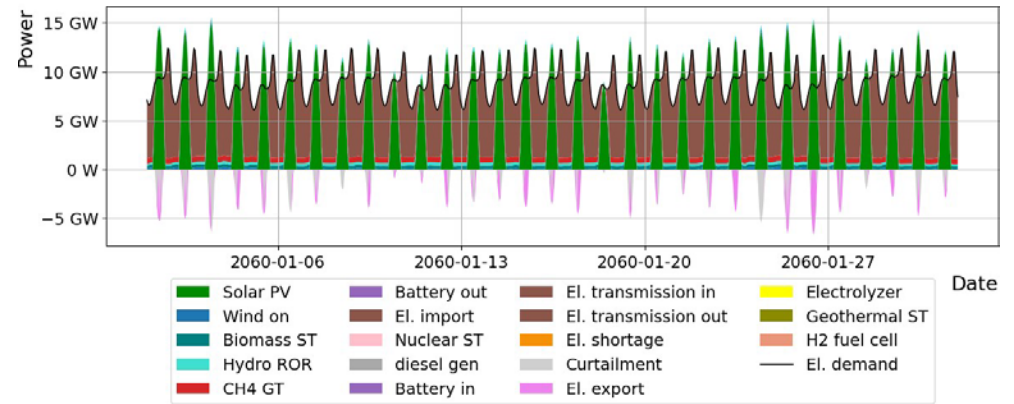
Figure 4.14 illustrates the contribution from all generations in 2060. It reveals that electrolyzer, hydrogen fuel cell (H2 fuel cell) and generation from solar PV takes over about 80% of capacities. While capacities from natural gas (CH4 GT), bioenergy converted from biomass, hydropower from a run of river and wind (onshore wind) are marginal they are also low-carbon sources. This implies that natural gas will be a part of the generation mix in the long term but its contribution is marginal in the modeling period.

The dynamics of low-carbon energy transitions and net zero transition plan toward Nigeria's energy security

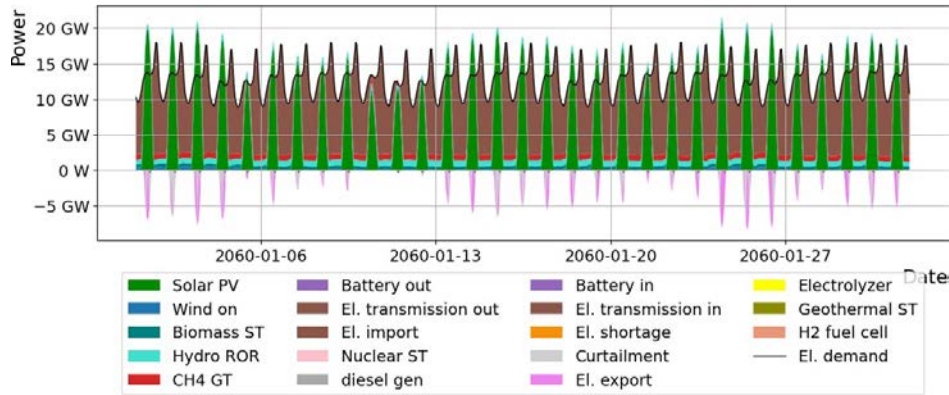
ABJ-electricity dispatch



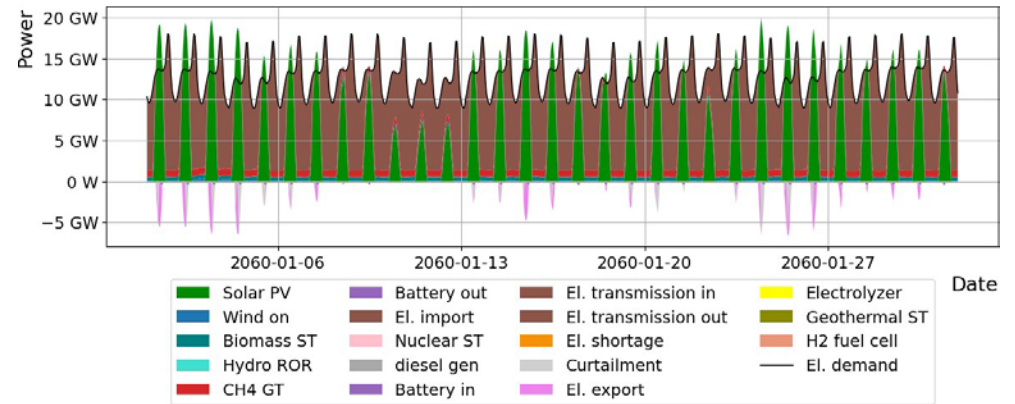
JOS-electricity dispatch



KAD-electricity dispatch



KNO-electricity dispatch



YOL-electricity dispatch

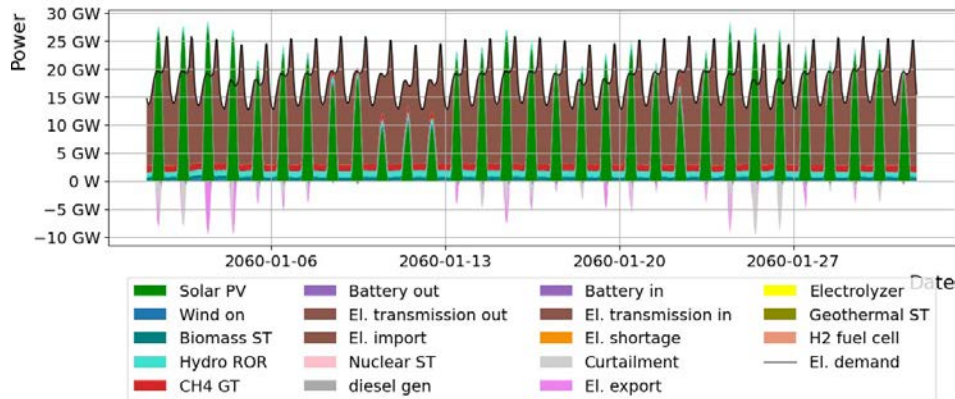


Figure 4.13. Hourly electricity dispatched for five DisCos in the Nigeria Power Industry for the month of January, 2060

Figure 4. 13. Hourly electricity dispatched for five DisCos in the Nigeria Power Industry for the month of January, 2060.

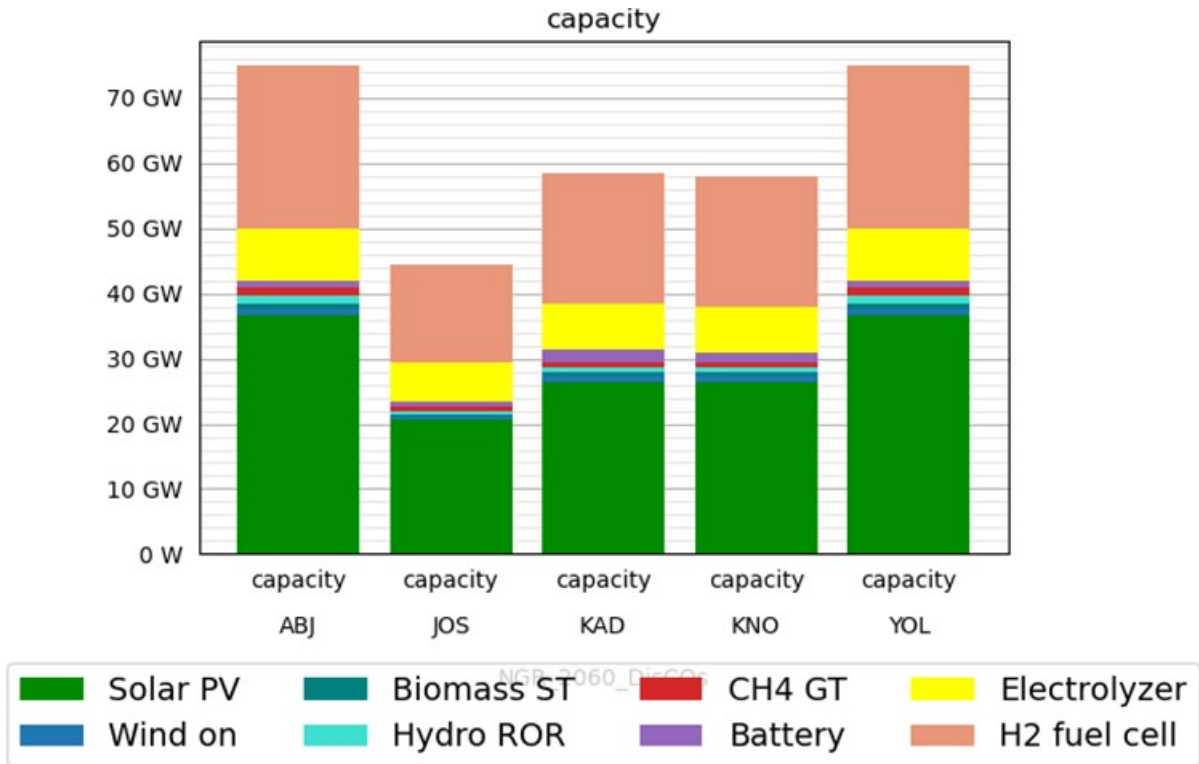


Figure 4. 14. Aggregated capacity across the Distribution Company by 2060.

4.5. Conclusions

This section concludes the chapter. It presents deductions from the analysis of an open energy modeling framework. This explores low-carbon energy system modeling for an energy transition plan and a distributed energy system framework.

It has shown that Nigeria's electricity demand is huge and a larger part of it is met by captive generation from diesel /petrol generator sets. The persistent use of diesel generator sets would go beyond the current situation till 2030 and 2045 and beyond. As the economy grows at different GDP growth rates, there will be a higher demand for energy infrastructure to meet demand. This will enhance the generation mix while minimizing greenhouse gas emissions. In the effort to achieve a net-zero emissions reduction target, natural gas will serve as a transition fuel, which is a major fuel for the short and medium term, while solar energy technologies will serve as the most accepted and relevant future driver of the technology mix. Also, the need for green hydrogen fuel cells to be among the technologies that drive the Nigerian green initiative in its net-zero emissions target will be heavily driven by a purposeful and deliberate investment in solar technology. Moreover, distributed generation with electricity transmission among distribution companies (DisCos) would help control excess electricity that would otherwise be wasted or lost. As the country makes net-zero emission plans, adopting a distribution generation

approach would better meet demand and enhance the integration of more clean energy technologies into the Nigerian energy mix.

Finally, the current study concludes that while energy from natural gas will be a short and medium-term driver solar energy will be the main clean energy initiative that would support the realization of a clean energy transition strategy in the long term. More so, a distributed generation approach would further restrain waste and reduce over-dependence on captive power generated from diesel/petrol generators. Gas, being a major future clean fuel in the Nigerian energy transition strategy should be well integrated and explored in the residential sector also. An integrated assessment of the energy sector and a transition fuel would support robust planning. On this note, the next chapter employs a systems dynamic approach to explore the clean cooking energy transition in Nigeria. It explores low-carbon development and policy implications for developing countries.

CHAPTER FIVE

CLEAN COOKING ENERGY TRANSITION IN NIGERIA: TOWARDS LOW CARBON DEVELOPMENT AND POLICY IMPLICATION FOR DEVELOPING COUNTRIES

5.0. Introduction

Within the last two decades, various international development agencies, national and local governments, and private sector entities have been working together to improve the diffusion of clean cookstoves among households (Hewitt *et al.*, 2018). These efforts are yet to deliver much-needed results in terms of pace and scale, as both the adoption and the continuous use of modern cookstoves remain low among households (IEA, 2020b). Furthermore, the current Coronavirus disease (COVID-19) has severely limited investment in modern energy systems, thereby pushing countries further away from achieving universal access to clean cooking. If the current trend is not improved, by 2030 clean cooking will still elude about 2.3 billion people, especially in Sub-Saharan Africa (SSA) (IEA, 2017b). This scenario shows that the challenge of clean cooking is not equally distributed worldwide. Specifically, rural areas in South America, developing Asia, and SSA are most affected (Bonan *et al.*, 2017).

Complexities exist as nations transition to clean cooking energy systems (Kumar *et al.*, 2016) because the systems exhibit unpredictable behaviours as they evolve. Complexities are predominant in the energy sector of emerging economies, primarily due to the dearth of data, lack of infrastructure, weak policy and institutional frameworks, inconsistent implementation of policies and legislation, and socio-cultural practices (Jagger *et al.*, 2017). These challenges have affected planning towards evolving energy systems and transition pathways relating to emerging nations' techno-socio-economic dynamics. Ensuring access to clean cooking in all households in developing countries will soon require robust policy reforms (Dioha & Kumar, 2020a). Aside from financing issues, one of the critical obstacles, limiting the massive transition to a clean cooking energy system in developing countries, is the lack of proper knowledge of the complexities surrounding its diffusion.

This study takes a closer look at Nigeria – a developing country and the most populous and largest economy in Africa (Dioha, 2020; Dioha & Kumar, 2020b). Despite the plethora of energy resources in the country, about 90% of Nigerian households still depend on traditional inefficient cook stoves for their domestic thermal energy needs (Dioha & Emodi, 2019), this suggests that there is a need to make a deliberate effort to invest in other cook fuel. The Nigerian government aims to provide its citizens with clean cooking equipment (FGN, 2016).

However, such an ambitious goal needs to be informed by a thorough understanding of the complexities surrounding the transition to clean cooking energy systems. Despite decades of existence and experience, the Nigerian energy sector still grapples with ensuring adequate clean cookstoves in urban and especially rural areas. This suggests the need for better adoption of clean cooking by the larger population.

Various scholars have inquired into the factors that influence the transition to clean cooking energy systems (Ateba *et al.*, 2018; Bisu *et al.*, 2016; Danlami *et al.*, 2018; Debbi *et al.*, 2014; Makonese *et al.*, 2018; Mensah & Adu, 2015; Nyankone, 2018; Paudel *et al.*, 2020; Rahut *et al.*, 2019; Sana *et al.*, 2020; Soltani *et al.*, 2019). A large percentage of these studies recognised household-level factors such as household size, level of education, household income, geographical location, fuel availability, the gender of household head, and change of seasons (Bisu *et al.*, 2016; Dagnachew *et al.*, 2019; Danlami *et al.*, 2018; Debbi *et al.*, 2014; Ozoh *et al.*, 2018; Soltani *et al.*, 2019; Vigolo *et al.*, 2018).

However, a critical assessment of the literature shows that studies employing a system dynamics approach toward assessing the nature of the clean cooking energy transition are scanty. Also, the majority of studies employ econometric models and survey results to assess the factors affecting the clean cooking transition. However, they do not consider the implications and feedback from a long-term perspective.

This study aims to advance clean cooking energy transition in the future. It explores how various factors will influence the transition to a clean cooking energy system using Nigeria as a case study. In this context, we develop and simulate the adoption of clean cookstoves, liquefied petroleum gas (LPG), as a modern fuel using system dynamics and the Bass diffusion model. LPG is considered a proxy for cooking fuel in the study because of its low emission factors with an insignificant impact on health. It also has significant penetration into the Nigerian household sector. At this juncture, it is imperative to stress that we do not intend to predict or forecast the evolution of clean cooking adoption in Nigeria. This study aims to generate a high-level understanding of how a clean cooking energy transition could occur from a long-term perspective in Nigeria.

We introduce one of the earliest case studies on clean cooking energy transitions based on a system dynamics model. By embracing a system dynamic modeling approach instead of conventional economic modeling, we have explored clean cooking energy transitions from a long-term perspective. Owing to the dichotomy of energy use in developing countries like

Nigeria, our study accounts for spatial heterogeneity by splitting households into rural and urban classes. We took it a step further by also providing policy implications. We believe that our analysis and findings will inform existing knowledge of the clean cooking fuel transition in Nigeria and other developing countries.

Section 5.1 of this chapter presents the study's theoretical framework and methodology. Section 5.2 presents the study results. Section 5.3 discusses the results, while section 5.4 wraps up the study with concluding remarks and policy implications.

5.1. The study's theoretical framework

5.1.1. The socio-techno-economic system of clean cooking transitions

Transition trends range from several perspectives and learning processes. The latter processes cut across the social, cultural, economic, and technical aspects of the shift. According to Cheap (Cherp *et al.*, 2018), three major factors shape energy transition: 1) economic development, 2) technological innovation, and 3) policy change. Thus, transition processes are multi-faceted (Geels, 2016) and require a systemic approach (Morecroft, 2018). In this study, the study explored the shift to clean cooking, considering innovative systems and co-evolution perspectives. These perspectives assume that changes occur across households and influence the transition to clean cooking (Yu *et al.*, 2019).

According to the World Bank (WB) assessment of clean cookstoves, about 179 million Nigerians lack access to clean cookstoves/technology (ESMAP, 2015). The WB study further suggested that a wide range of factors influence each household's cooking energy choices. These closely interrelated factors include socio-economic circumstances, fuel availability, cultural phenomena, environmental considerations, cookstove characteristics, and government policy (Johan-Schot, 2020). Some other scholars (Li *et al.*, 2015) have emphasised the interconnected relationship between the aforementioned factors and the socioeconomic and technical dimensions to transition pathways. These factors are further simplified according to their underlying variables, as shown in Figure 5.1.

Figure 5.1 shows a pseudo-connector for clean cooking parameters. It suggests ways these parameters could be interconnected to form a system driven by policy. The framework in Figure 5.1 describes a clean cooking transition management scheme that illustrates the sustainability concept of transitioning to clean cooking. Sustainability theory elements - social, economic, technological — form immediate feedback among infrastructure, demand for clean cooking in households, supply-demand, and urbanization.

The connecting arrows suggest that transitioning to clean cooking follows a systemic pattern. This implies that one part of the system parameter affects the other parts' outcomes in a continuous loop. Modeled outcomes from the interactions would also influence government policy in the transition domain. Therefore, these connections are necessary for decision-making to support holistic legislation for clean cooking transitions.

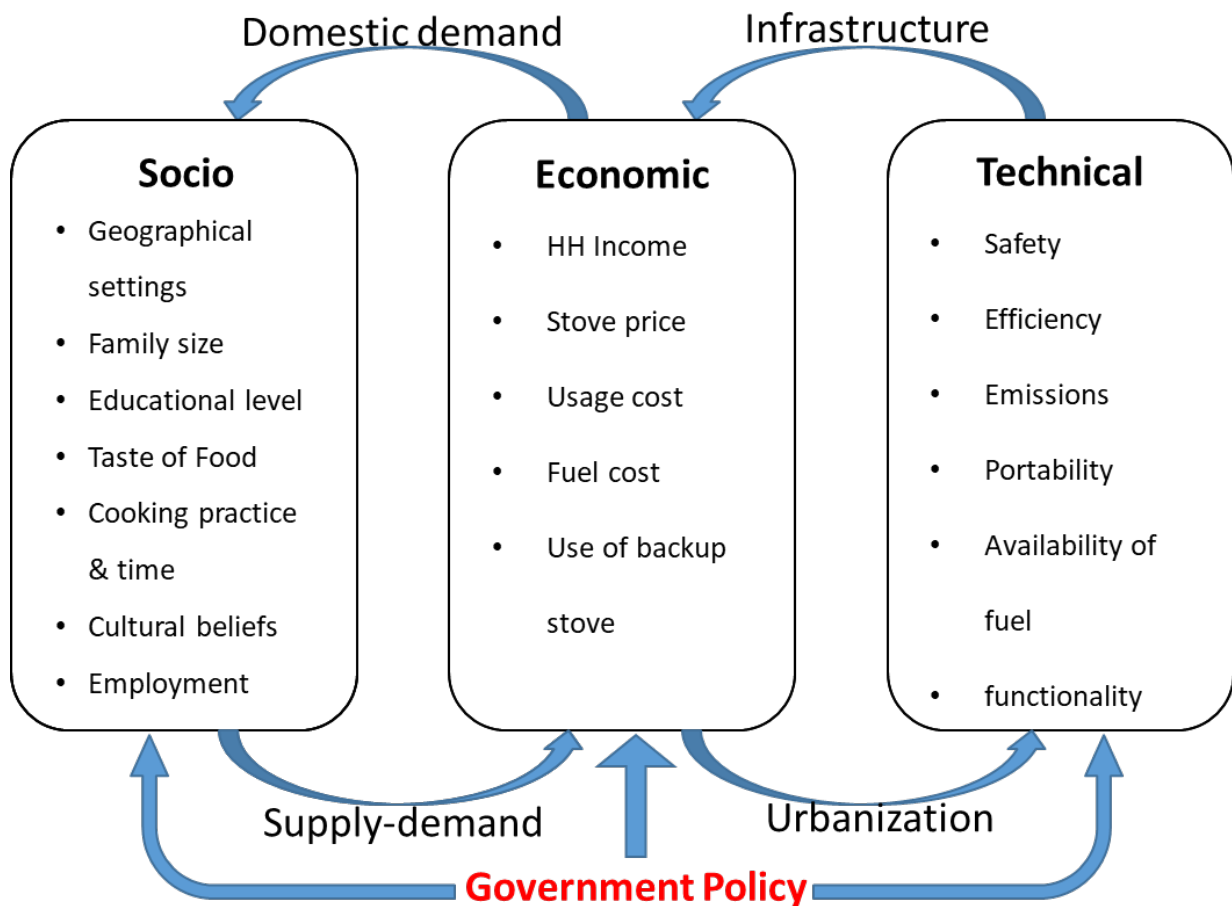


Figure 5. 1. Overview of clean cooking transition management model.

Note: The acronym HH, in the figure, stands for household.

To this end, we employ a Bass innovation and diffusion model, commonly used to study system dynamics (Zhao & Zhang, 2018). Bass-System dynamics consider the following model approach:

- i. A qualitative system thinking approach — to study interconnections and some feedback between variables to explain innovation theory, such as interconnectedness between market and technology in business and other techno-economic fields (Forum, 2021). This enhances system motivation, learning processes, strategies, and quantitative elements, such as fuel price, energy demand, and technology efficiency.

This is without compromising other impacting factors.

- ii. A quantitative system approach — to explore system behaviour as it changes with time and, thus, shows significant trends by quantitatively assessing policy/control points (leverage points) for legislation and decision-making.

5.1.2. Study Framework and Assumptions

The theoretical framework of this study is rooted in the Bass diffusion model and system dynamics. According to Bass (Bass, 1969), the Bass diffusion model aims to ascertain the number of customers/consumers willing, eventually, to adopt a new product or service. This study considers a composite model, an integrated Bass model, and system dynamics. A twin-like model is used to depict the structural analysis of rural and urban household consumers of clean cookstoves as consumer behaviour changes over time.

The Bass diffusion model assumes the following:

- i. that diffusion process is dualistic, *i.e.*, consumers either adopt or do not adopt a product;
- ii. that there exists a constant maximum potential number of consumers at a particular time;
- iii. that all potential consumers will eventually adopt the product over time;
- iv. that there is no repeat purchase or replacement of the product
- v. that the impact of word-of-mouth is independent of adoption time; and
- vi. that there is no substitute product.

However, there are some limitations to the Bass model. First, there is a tendency to exaggerate the behaviour of the system under study. This means that, in reality, not all potential consumers would ultimately adopt a product, as unforeseen events could prevent potential consumers from adopting a product initially intended to be adopted. Second, the Bass model cannot handle fluctuations/variabilities such as uncertainties in the adoption processes.

5.2. Methodological framework of the study

5.2.1. Conceptual framework of the model

The system dynamics (SD) model is relevant for analysing complex systems because it helps to understand mental models through the use of the Causal Loop Diagram (CLD) (Azar, 2012). The CLD uses system thinking practices and mental models to explain causality among interacting variables (Maani & Maharaj, 2004). Thus, it enables a clearer picture and understanding of systemic feedback for complex decision-making and policy analysis. The

primary purpose of SD methodology is to understand the causes of undesirable dynamics and design new policies to ameliorate them. Undesirable outcomes are produced from the dynamic behavioural patterns of the system variables. This means that the structure creates the behaviour that influences the system boundary (Shari *et al.*, 2020b).

5.2.2. The Bass model and its mathematical formulation

The Bass model, named after Frank M. Bass (Bass, 1969), posits that diffusion processes are uneven and evolve as innovations are communicated through certain systems over time (Maier, 1998). Several researchers have used diverse models to explore the concept of diffusion of innovations in literature, applicable to different sectors such as health and agriculture (Horvat *et al.*, 2020; Naji & Hussien, 2016). Many of these models are based on Frank M. Bass' model of innovation diffusion (Bass, 1969; Milling & Maier, 2017). According to the Bass model, product purchase emanates from two human buying behaviours: 1) innovative purchase behaviour; and 2) imitative purchase behaviour. They can respectively be calculated using two important decision factors: i) coefficient of innovations

(p) – coefficient of external influence; ii) coefficient of imitation (q) – coefficient of internal influence. The general classical Bass equation model is therefore given, according to Equation (5.1) as

$$N = P \times (N - X_{t-1}) + q \times (X_{t-1}) \times (N - X_{t-1}) \quad (5.1)$$

Where N = Number of consumers who will purchase the product at a time (t)

$N - X_{t-1}$ = Remaining market potential

X_{t-1} = Adopters of product S_t until period $t - 1$ represented by $\sum_{t=0}^{t-1} S_t$

p = coefficient of innovations

q = coefficient of imitation

Equation (5.1) implies that consumers will adopt a new product or products that are yet to gain general acceptance in the market through i) marketing strategies such as adverts and ii) imitating existing product or initiative users as imitators.

Equation (5.2) shows the mathematical calculation modelling innovators' buying behaviour.

$$S_t^{inno} = p \times \left(N - \sum_{t=0}^{t-1} S_t \right) \quad (5.2)$$

The coefficient of innovation is a constant that represents the fraction of innovators of the remaining market potential at any point in time. On the one hand, innovative purchasers are not influenced by the number of purchases in the past. Instead, they make their purchasing

decision based on the spread of the product in the marketplace, i.e., through adverts. They are often called potential adopters of a product or innovation. On the other hand, imitative purchasers are those influenced by the number of purchases in the past. This means that the more customers have adopted the product in the past, the higher the social pressure to purchase it. Imitative purchases over a period of time can be calculated according to Equation (5.3).

$$S_t^{imit} = q \times \frac{\sum_{t=0}^{t-1} S_t}{N} \times \left(N - \sum_{t=0}^{t-1} S_t \right) \quad (5.3)$$

The total product adopted in a time (t) can be expressed as the sum of innovative and imitative purchases given in Equation (5.4). This expression shows the product life cycle behaviour of a product's spread in the marketplace.

$$S_t^{tot} = S_t^{inno} + S_t^{imit} = p \times \left(N - \sum_{t=0}^{t-1} S_t \right) + q \times \frac{\sum_{t=0}^{t-1} S_t}{N} \times \left(N - \sum_{t=0}^{t-1} S_t \right) \quad (5.4)$$

Equation (5.4) describes the time pattern a product follows through subsequent stages of introduction, growth, maturity, and decline according to an S-shape growth.

However, it is essential to note that, in reality, coefficients p and q are independent of any changes in the adoption of innovation over time (t). Also, in the classical Bass model, the coefficients p and q are constants independent of other decision variables, such as price, income, and educational level (Milling & Maier, 2017). This independence of variables is a severe shortcoming of the classical Bass model since, in reality, diffusion and transition pathways are strongly influenced by feedback. Therefore, this non-interconnection among influencing variables poses a limitation to utilizing the classical Bass model. This is because it does not include feedback mechanisms between the diffusion process and other variables that could be useful for decision-making and policy development. To mitigate this shortcoming, we applied the extended Bass model using the SD simulation paradigm. The SD quantitative and qualitative model would then be used to model and simulate the Bass innovation and diffusion model. This would be done by extending the classical Bass model earlier explained in Equations 1, 2, 3, and 4.

5.2.3. System dynamics formulation of the Bass model

Application of SD to the Bass model is relevant to explaining reasons for non-linearities in adopters' preferences to transit to other products or services. In this study, the LPG stove represents the product to be adopted. When would its adoption be at its maximum, and when would it begin to lose market value/share, i.e., when would its adoption mature? Models developed in this fashion can serve as simulators to analyze the consequences of strategies. They can also understand what policy design would improve clean cooking adoption among Nigerian households/consumers.

Figure 5.2 shows a simulation of the SFD of the classical Bass model. It depicts the fundamental simulated structure of the Bass model built upon Equation (5.4). Market potential and accumulation of adoption are represented by the stock component of a simulated version of the Bass model in Figure 5.2.

According to Figure 5.2, the stocks represented by the potential adopters and cumulated adopters are mathematically expressed as $N - X_{t-1}$ and X_{t-1} , respectively. The sum of adoption in Equation (5.4) is represented by the adoption rate, while the innovative and imitative purchases are represented as innovative adoption and imitative adopters, in that order. Therefore, an integrated SD and Bass model shed important insights for energy policy toward local energy transition (Selvakkumaran & Ahlgren, 2020; Zhao & Zhang, 2018), including the transition to clean cooking (Chalise *et al.*, 2018; Kumar *et al.*, 2016).

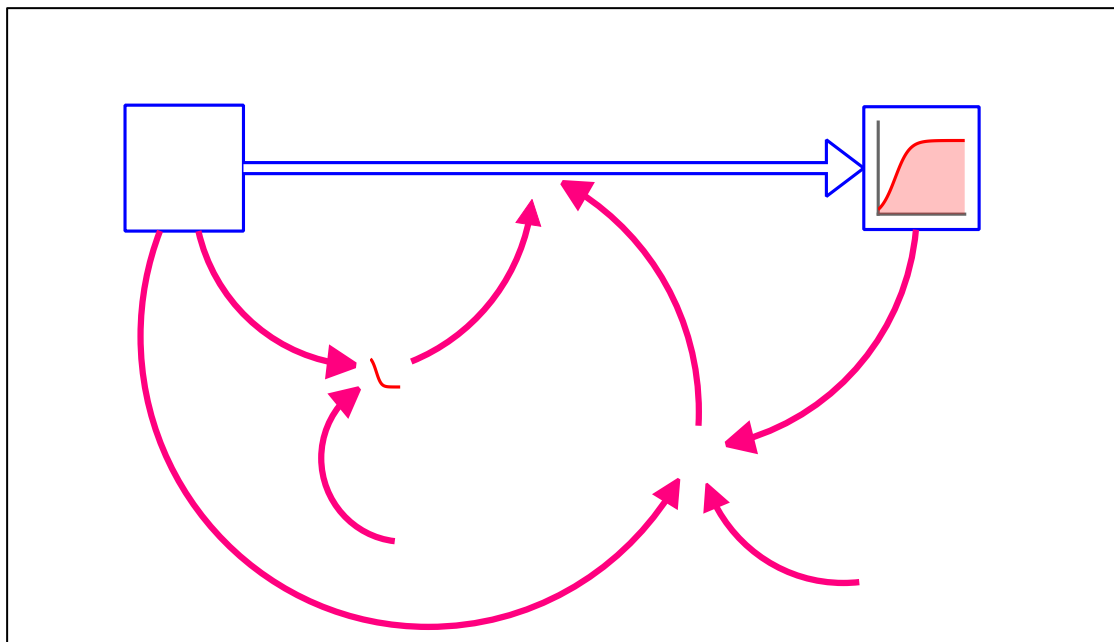


Figure 5. 2. An idealized simulated stock and flow diagram of the classical Bass model.

5.2.4. Building the Model

In this study, the SD model was divided into two stages: i) a qualitative model, viz., a mental model to guide the development of the stock and flow simulation model and ii) a quantitative model. The latter model formulates the model equations and performs the subsequent simulation through the stock and flow diagram (Maria, 1997). The simplistic SD mental model was developed in collaboration with experts from the Nigerian energy sector as per the underlying structure of the clean cooking adoption. The model was built using STELLA professional software, Version 1.3.1.

The confirmation of the theoretical structure test verified if the stock and flow structures were consistent with the knowledge of the system under scrutiny (Horvat *et al.*, 2020). A structured review of literature on clean cooking transition, using LPG as an energy carrier, was carried out for model building. To assess the model's performance, variables obtained from the literature review and the structure of the SFD were evaluated for consistency. After the model was formulated, the dimension and unit consistency were ensured and done accordingly (Barlas, 1996). Furthermore, to establish consistency and observe significant trends, sensitivity analysis was performed (presented in the result section) (Hearne, 1987). Also, a structural behaviour test was performed. To corroborate the accuracy of the structural behaviour analysis, the simulated model needed to show an S-shaped structural behaviour, while reaching the value of the maximum cumulated adopters or reduction in the potential adopters that are in the stocks. These tests were to make sure that behavioural familiarity and consistency (Turner & Kim, 2014) with the Bass model and guarantee equation consistency in the SFD. Finally, calibration of the model was performed.

5.2.5. Developing the Causal Loop Diagram

Figure 5.3 displays the main feedback loops of a generic simulation model developed to provide insight into dynamics. The two rectangular boxes represent sector loops, i.e., diffusion, impact, and sector loops' drivers. Simultaneously, the 'R' and 'B' displayed in different colours are reinforcing and balancing loops, respectively. By reinforcing and balancing the loops, diffusion, and innovation of clean cooking using LPG are intrinsically limited or enhanced. The impact and drivers of sector loops are expected to have the same effect.

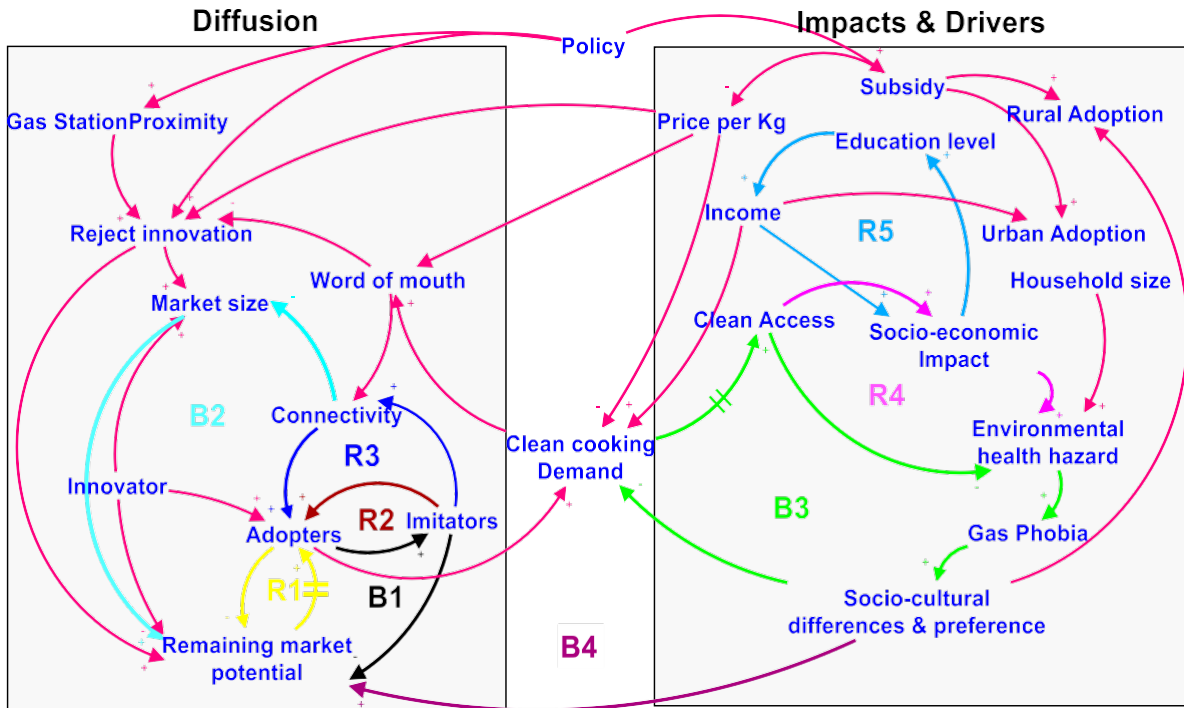


Figure 5. 3. Causal loop diagram for the adoption of LPG clean-cook stove

This intrinsic characteristic means that there is no constant growth in the system's structural behaviour, i.e., our actions and inactions determine the system's dynamics. To buttress this, the continuous growth encountered due to reinforcing loops R1, R2, R3, R4, and R5 would counteract such persistent growth by balancing loops B1, B2, B3, and B4. As a result of increased income (R5), clean cookstoves are adopted due to reinforcing and balancing loop structures. In contrast, the fear of using gas as a cooking fuel (gas phobia) expressed in B3 would counterbalance the expected continuous growth due to increased income.

5.2.6. Developing the Stock and Flow Diagram (SFD)

The SFD shown in Figure 5.4 illustrates a diffusion and composite model comprising rural and urban areas. The SFD further shows the spread or diffusion of clean cookstoves.

This section entails analysis from potential adopters to adopters. Figure 5.4 shows the integrated SFD model of clean cooking adoption in Nigeria. The SFD is composite as it indicates the modelling dynamics of clean cooking in the Nigerian urban and rural household's sector. The composite model considers some assumptions: 1) that rural and urban household areas have the same model equations and structural behaviour and 2) that they are differentiated by variances in the calibration process due to differences in data input.

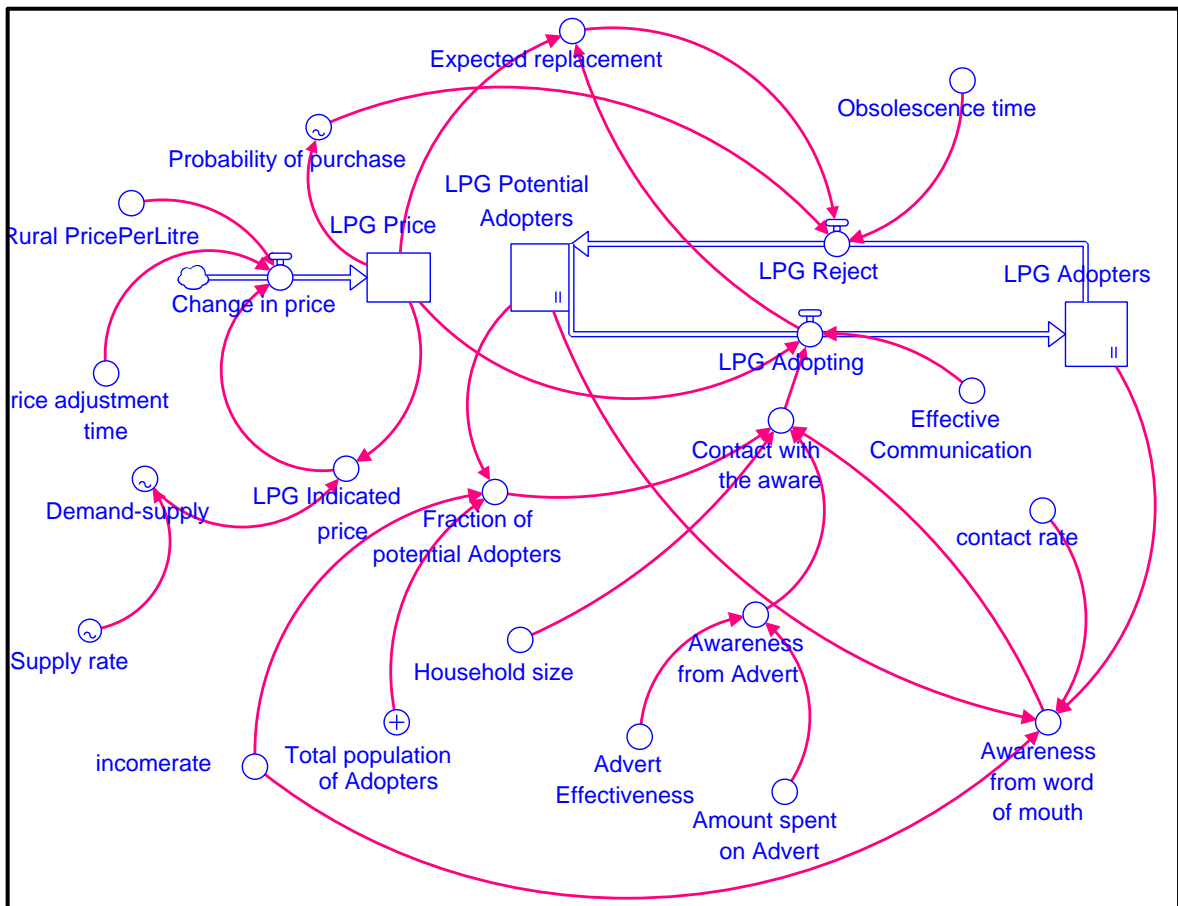


Figure 5. 4. Stock and flow diagram of an innovation and diffusion model for clean cooking transition.

The development of the composite model starts with the influence of homogenous variables, which determine imitators' and innovators' adoption rates. Such homogenous variables include adverts, promotional activities, and word-of-mouth information. The model variables are represented in the SFD (Figure 5.4) as advert effectiveness, awareness through word-of-mouth, and contact with the 'aware'⁴², respectively. The innovators start the system with potential adopters through promotional activities, then imitators who later spread information about the innovation by word-of-mouth. However, not all households that contact potential adopters will become adopters. The converter, effective communication, models the practical impact of word-of-mouth on potential adopters. For word-of-mouth to be effective, potential adopters need to be aware of the product or innovation in the market space as innovators. This would enable potential adopters to imitate the product and adopt such innovation.

⁴²The 'aware' as used in the model refers to those households who are informed about liquefied petroleum gas as a clean cooking fuel but have not necessary adopted the technology.

Furthermore, to create confidence in the model, the study follows a systematic approach that links sensitivity, calibration, and uncertainty analysis (Tian *et al.*, 2016). A sensitivity approach was employed for the process of scenario analysis. The model's uncertainty analysis was implemented utilizing the Monte Carlo simulation process. The Monte Carlo process was then engaged in the model tab of the STELLA software. Simultaneously, the structural calibration scheme was used to estimate various parameter values in the model. Data obtained from the Nigerian Liquefied Petroleum Gas (NLPG) report (LPG Summit, 2019) were used to calibrate the base run model because LPG consumption and its proliferation among households exhibited steady growth trends. These trends were favourably compared to the base run.

5.2.7. Description of dynamic scenario

Table 5.1 presents the description of the study scenarios. According to Table 5.1, Four scenarios are described. Scenario one (S1) describes the household income rate, and scenario two (S2) describes the household size. Scenarios three and four present the price of Liquefied Petroleum Gas (LPG) and Contact rate (S4), respectively.

Table 5. 1.Description of four scenarios as simulation experiments.

Scenario	Description
Scenario (S1) Household income rate	Scenario 1 tests the effect of an increase in household income compared to the base run and its influence on the potential adopters, adopters, adoption rate and rejection rate.
Scenario (S2) Household size	Scenario 2 tests the effect of a decrease in household size compared to the base run. This scenario addresses how the potential adopters, adopters, adoption rate and rejection rate would evolve due to changes made to the household size.
Scenario (S3) Price of LPG	In Scenario 3, the effect of a decrease in LPG price compared to the base run was carried out. In this case, changes in LPG prices were modelled by considering the impact on the number of rural and urban households that adopt or reject clean cooking
Scenario (S4) Contact rate	In scenario 4, the effect of changed "contact rate" to adopt clean cooking, compared to the base run, was considered. In this scenario, an increase in households' contact rate with adopters was modelled.

5.3. Results

5.3.1. Base-run model simulation

The base-run simulation is shown in Figure 5.5. It presents the behaviour and transition of potential adopters and adopters of clean cooking from 2010 to 2050 in the simulated SD model. The developed SD model was calibrated for urban households as follows: 7 million total urban households, average household size at 6, household income rate at 8.5%, contact rate at 5%, and 1.5% effective communication among urban households [19, 60]. For rural households: 9.94 million households, 8 persons per household, income rate of 7.5%, contact rate of 8.3%, and 0.85% effective communication among rural households (Apata, 2016). The composite model has considered a price of 1.31 USD per kg of LPG (Nwachukwu, 2011). It is important to note that these data are for experimental purposes only as their precise future evolution is uncertain. The model has a running period of 41 years, with a start in 2010 and an end date of 2050. This model does not include Nigeria's population changes during the simulation period. This hypothesis was made to simplify the quantitative interpretation of SD model results, where the exact value of stocks at the end of the model run is not as significant as the shape of the curves, suggesting clean cooking transition system behavior. The base run also assumes that all conditions and parameters are constant without alteration or adjustment.

Base Run Simulation Clean Cooking Adoption

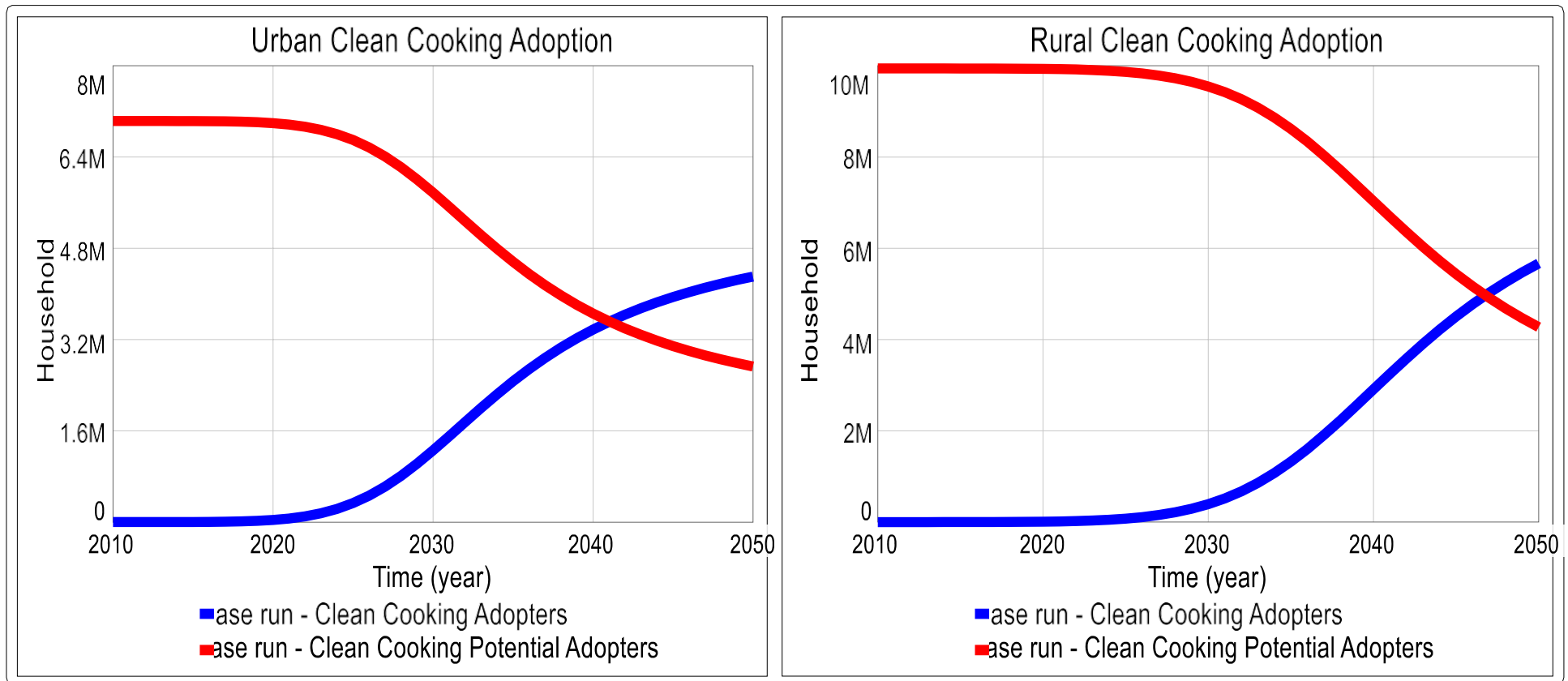


Figure 5. 5. Base-run model behavior.

The simulated base run represented in Figure 5.5 (showing changes in the main stocks on the adoption of clean cooking in Nigeria) shows that clean cooking diffusion is slow at the beginning. However, it peaks in the middle of the simulation period. At the same time, the stock of potential adopters depletes slowly. However, similar simulation trends were observed in both rural and urban households. A decline or reduction in the number of potential adopters leads to the growth or addition of clean cooking adopters. This decline in potential adopters suggests that about 1.35 million urban householders will adopt clean cookstoves by 2030. This would leave about 5.68 million households without access to clean cooking facilities. This implies that around 23.7% of urban households will have clean cookstoves by 2030. Besides, a sharp decline in potential adopters was observed in 2034 in the base run. This means that more households will naturally transition to clean cookstoves without legislative efforts. Still, such a transition may take longer to achieve cooking energy access.

On the other hand, rural households may consider implementing the practice of clean cooking later than urban households. Here, a sharp adoption of clean cooking was observed in 2032 as against 2026 among urban households. This suggests that the slow adoption rate among rural households could slow down the transition to clean cooking in Nigeria. The base-run simulation (Figure 5.5) is also called a business-as-usual scenario. It depicts how the shift to clean cooking in Nigeria would evolve without controlling some influencing parameters. In 2040 and 2047, urban and rural households would experience equilibrium between potential adopters and adopters. This three-year difference in potential adopters and adopters making a tie illustrates the discrepancy among adopters according to their spatial settlements. At the end of the simulation period, the result shows an intriguing narrative – about 37% and 45% of households in urban and rural areas, respectively, would not be able to become adopters by 2050. This, therefore, suggests reasons for non-linearities in the modeling outcome, thereby presenting the case that not all households (both in the metropolitan and rural areas) would have transitioned to clean cooking by 2050 in the base-run simulation. Figure 5.6 shows a comparative analysis of clean cooking adoption in rural and urban households. Further, Figure 5.6 reveals that there will be an equilibrium among urban and rural adopters in 2043. By 2050 a 45% and 14% increase will be experienced among rural and urban household adopters, respectively, relative to the equilibrium year.

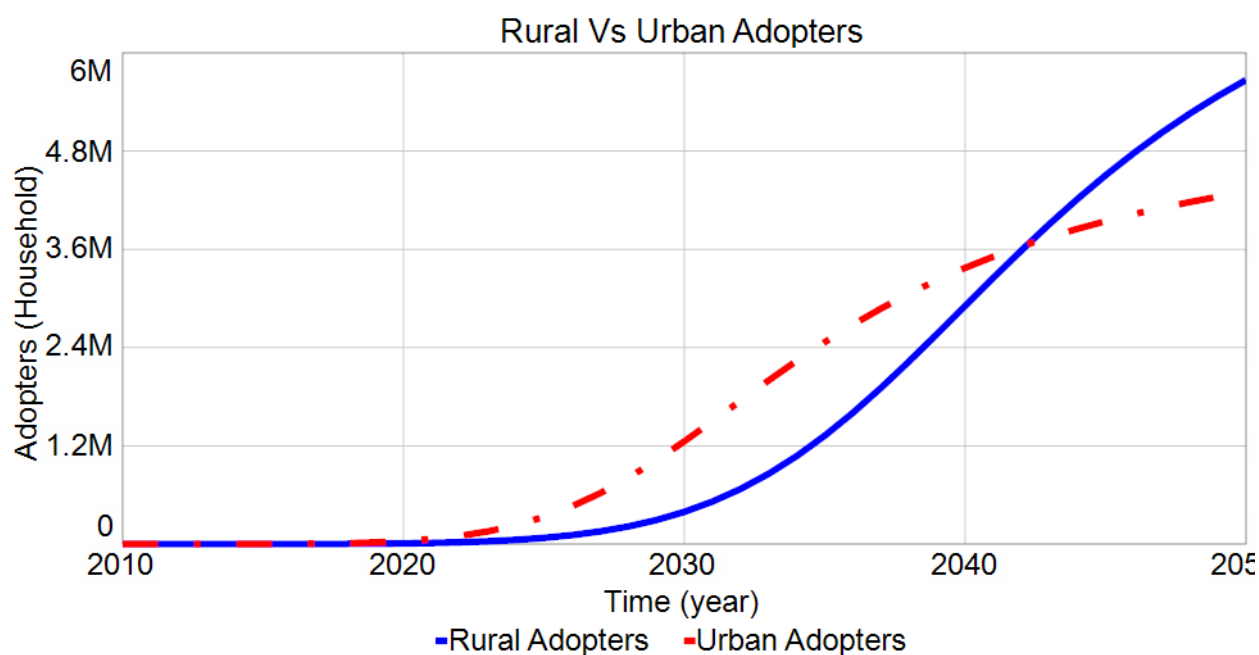


Figure 5. 6. Comparative analysis of rural and urban adoption of clean cooking.

5.3.2. Analysis of scenarios

This study proposes four simple scenarios (shown in Table 5.1) to study the influence of changes in various model variables on adopting clean cookstoves in the Nigerian household sector. The model has considered scenarios for rural and urban household consumers, remembering that variables we adjusted in the study can be influenced by the reality. The variables considered in the model (shown in Figure 5.4) are for experimental purposes (however, obtained from reliable sources as initially discussed), as they could have different values in real-life applications. Each scenario targeted four variables, with sensitivity analysis carried out on each variable to establish a clear connection between the parameter change and system behavior.

Figures 5.7 and 5.8 show scenario analyses for rural and urban household clean cookstove adoption, respectively. In the analysis of scenarios, we have considered sensitivity analysis of the following variables (or leverage points): 1) the first scenario (S1) – household income rate; 2) the second scenario (S2) – household size; 3) the third scenario (S3) – LPG price per kg; and 4) the fourth scenario (S4) as contact rate (see Table 5.1). The analysis of scenarios was also conducted based on the influence of leverage points on the i) clean cooking potential adopters; ii) clean cooking adopters; iii) clean cooking adoption rate; and iv) clean cooking rejection rate. This means that the analysis within the stocks and flows captured behavior and trends due to changes in the leverage points. Sensitivity analysis was done at leverage values of 25% and 50% increase or decrease. The sensitivity value at 25% was labelled as moderate, and the sensitivity value at 50% as optimum.

Rural Scenario Analysis

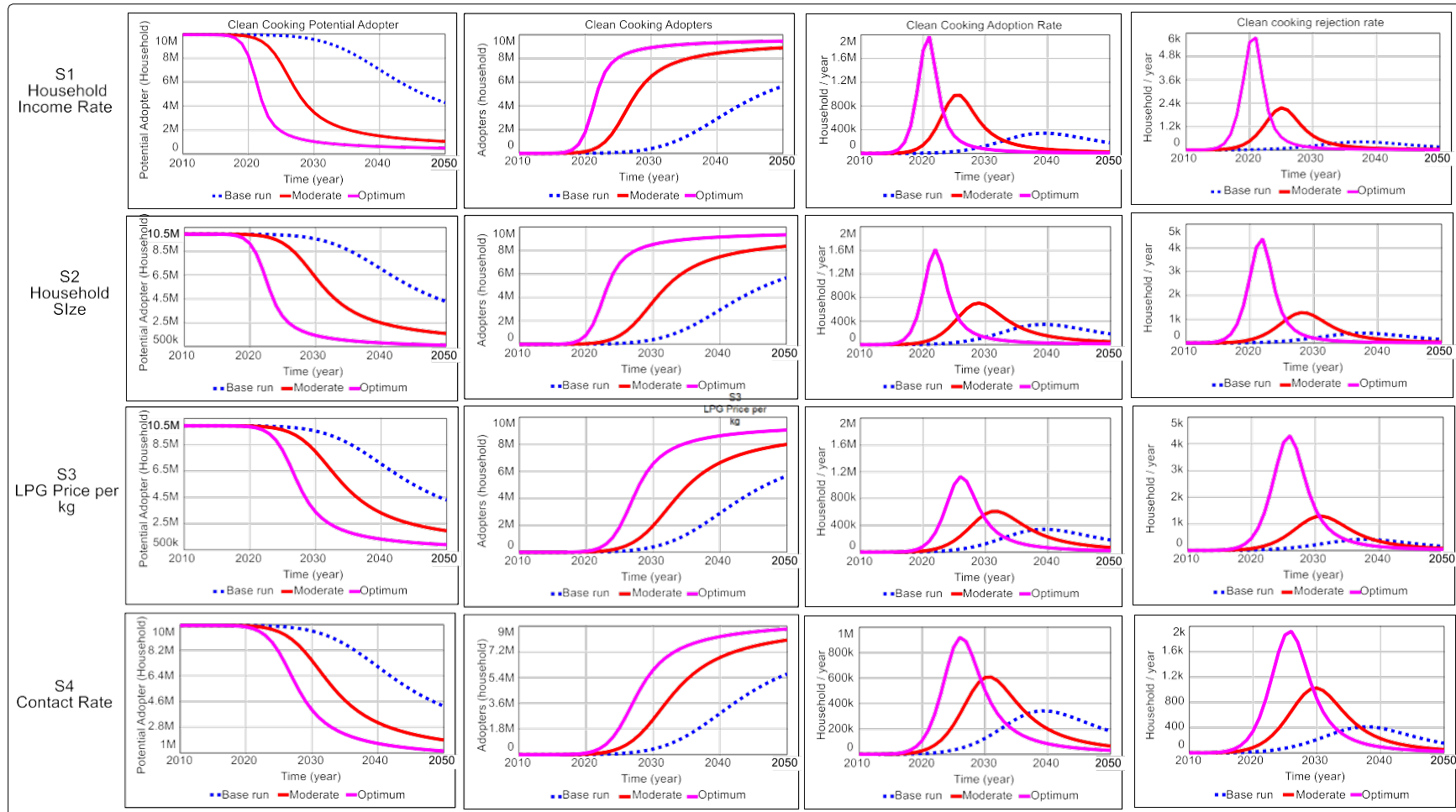


Figure 5. 7. Behavior of "Potential adopters", Adopters, Adoption rate and Rejection rate stocks and flow rate.

Urban Scenario Analysis

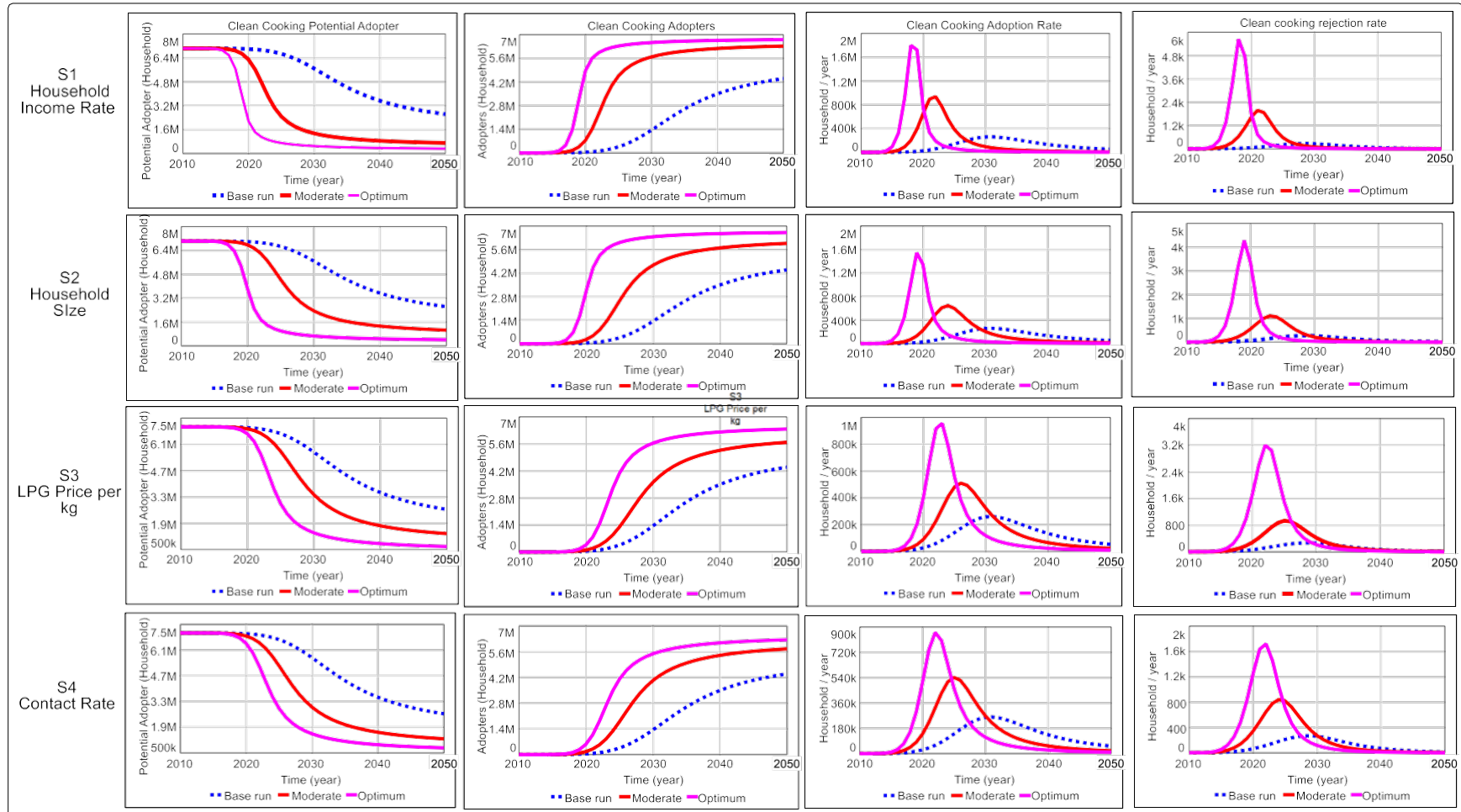


Figure 5. 8. Behaviour of "Potential adopters", Adopters, Adoption rate and Rejection rate stocks and flow rate.

5.3.2.1. Analysis of rural scenarios

Scenario 1 (S1): Results from Figure 5.7 show a reduction in both moderate and optimal trends in the total number of clean cookstove potential adopters due to increased household income rates. Consequently, about 1.04 million households in the moderate trend fail to use clean cookstoves. In comparison, approximately 487 thousand rural households would be left to utilize clean cookstoves in the most efficient manner by 2050. This suggests a 75.64% decrease and an 88.59% decrease in the moderate and optimum run compared to the base run. Also, changes in rural household income suggest that if a modest change is made in household income, about 8.9 million households will adopt clean cooking. In contrast, in an ideal scenario, approximately 9.45 million households would have adopted clean cooking. This growth in adopters can be attributed to household income increases. Thus, the more income a household earns, the more likely they are to engage in clean cooking.

Furthermore, the rate at which rural households would adopt or reject clean cooking due to an increase in rural household income is shown in S1. This illustrates that adoption would occur at a rate of 26.50 thousand and 8.83 thousand rural households per year at moderate and optimal household income changes, respectively. This suggests that the adoption rate towards 2050 will decrease because few households adopt clean cookstoves in the long run. Also, in terms of clean cooking rejection rate, about 22.50 and 7.49 rural households at moderate and optimum changes, respectively, would reject clean cookstoves per annum. The apparent differences noticed in the changes between adoption and rejection rates could be because, as rural household income increases, more households would adopt clean cookstoves at a rate that surpasses their rejection. Similarly, changes in the adoption rate across the two sensitive trends suggest that adoption will occur earlier with increased household income, with more households transitioning to clean cooking in the optimum run than in the moderate run. The decreased rate could further be attributed to the fact that fewer households would adopt clean cookstoves in the future, as the total population of households yet to adopt would have reduced.

Scenario 2 (S2): Under this scenario, rural household size reduces. In the rural household size scenario, about 1.59 million and 610 thousand households in the moderate and optimum runs, respectively, would remain as potential adopters. This represents about a 62.75% reduction in the moderate run and an 85.71% reduction in the optimum run compared to the base run. This reduction in the total number of households yet to adopt clean cookstoves suggests that, at smaller household sizes, adopting clean cookstoves would be higher with fewer households as potential adopters. The result, therefore, shows that, despite the reduction in household size, not all potential adopters of clean cookstoves would become

final adopters. This could be attributed to why household size changes might not incentivize rural households' total transition to environmentally friendly cooking. In contrast to the analysis of potential adopters, the analysis for adopters due to changes in household size shows an adoption rate of about 8.35 million households and 9.33 million households, representing an increase of approximately 47.27% and 64.55% in the moderate and optimum runs, respectively, compared to the base run. A growth in adopters due to small household sizes further suggests that smaller household sizes would adopt cleaner cookstoves than larger household sizes. This is because cooking choices and preferences are limited to smaller household sizes.

Scenario 3 (S3): For the third scenario, Figure 5.7 shows that about 1.95 million and 890 thousand households in the average and optimum runs, respectively, would be potential adopters. About 54.54% and 79.25% of the reduction compared to the base run are households yet to switch to clean cookstoves. Conversely, the adoption of clean cooking in the moderate and optimum runs shows that about 7.99 million and 9.05 million households would adopt clean cookstoves. This represents a 41.17% and 59.89% increase in adopters compared to the base run. The low growth observed in clean cookstove adoption indicates a small relative change in the moderate and optimum runs. This is despite reduced LPG prices. The study argues that LPG prices might yield minor changes in clean cooking adoption processes, probably due to higher preferences for alternative cookstoves. This scenario further suggests that if income levels are not increased, reducing LPG prices alone will have little effect on clean cooking adoption.

Furthermore, sensitivity analysis on adoption rate due to price changes shows that between 70 and 24 thousand households per annum would switch to clean cooking. As a result, about 61.59% and 86.81% decreases per annum are recorded in the moderate and optimum runs, respectively, compared to the base run. This decrease in the adoption rate among simulation runs implies that, as more households shift to a clean cookstove, fewer households would be left to transition in later years. Interestingly, simulation results showed that more households would switch to clean cooking due to reduced LPG prices. Simulation results also show that 78.2 and 38.9 households reject clean cooking. This represents about 49% and 74% reduction in the moderate and optimum runs, respectively, compared to the base run. The lower values observed in the rejection rate suggest that the shift to clean cookstoves would be experienced faster than rejected in later years. This is due to decreased LPG prices per kg.

Scenario 4 (S4): The fourth scenario, according to Figure 5.7, represents the effect of contact rate on adopting clean cookstoves in Nigerian rural households. Around 1.90 million and 1.14 million households still do not have clean cookstoves at moderate or optimal speeds, thanks to the increased contact rate. This represents a 55% decrease in the moderate run and a 73% decrease in the optimum run compared to the base run. This implies that fewer households would remain potential adopters. The ideal scoring is low for the number of households yet to shift to clean cooking. In addition, around 8.03 million and 8.80 million rural households would have switched to clean cookstoves in the moderate and optimal scenarios among clean cooking adopters, respectively. This means an increase of about 42% and 55% of households adopting clean cookstoves, compared to the base run at the end of the simulation period. Moreover, additional analysis on S4 (Figure 5.7) shows that around 64.5 thousand and 30.3 thousand households per year would adopt clean cookstoves. This means that an improvement in contact rate among rural households would reduce the number of households left to shift to clean cooking. This would be at a reduced rate of about 65% and 83% of households per year in the moderate and optimum runs, respectively. This is compared to the base run. On the other hand, around 54.6 and 25.6 households per year would reject clean cooking at moderate and optimum runs. However, similar percentage decrease trends were observed in the adoption and rejection rates at the moderate and optimum runs of S4. This suggests that a decrease in the adoption and rejection of clean cooking occurs at the same rate at the end of the simulated period. However, it occurs at different quantitative low values for households in the rejection rate.

5.3.2.2. Analysis of urban scenarios

Figure 5.8 shows the analysis results for urban scenarios. Scenario analysis follows the same parameters subjected to sensitivity analysis as in rural scenarios. Model calibration values differ significantly in the urban model.

Scenario 1 (S1): In scenario one, the impact of urban household income on those yet to switch to clean cookstoves (potential adopters) reveals that around 708 thousand and 329 thousand households would switch to clean cooking fuel by 2050. Thus, about 73% and 87% of households on moderate and optimal runs, respectively, would remain potential adopters compared to the base run. Urban households that are yet to adopt clean cooking are further clarified by analyzing households that have implemented clean cookstoves. In the same scenario, around 6.32 million and 6.70 million households in the moderate and optimum runs,

respectively, would switch to clean cookstoves. Compared to the base run, an increase of about 44% of households in the moderate run, while an increase of about 52% of households in the optimum run would adopt clean cooking at the end of the simulation period. In rural households, a rise in household income results in a more favorable shift to clean cooking than in urban households. However, results from the scenario trends reveal that urban households adopt faster in time. They show that more households are transitioning to clean cooking than rural households at the end of the simulation period. In addition, the results demonstrate that urban households' adoption and rejection rates display a similar trend as observed in rural households where few households refused clean cooking at the end of the simulation period. Analysis results from S1 in urban households show that an increase in urban household income would encourage clean cookstove adoption.

Scenario 2 (S2): In the urban household size scenario, results show that around 1.06 million and 414 thousand households in the moderate and optimum runs, respectively, would become potential adopters at the end of the simulation period. This means about a 60% decrease in the moderate run and an 84% decrease in the optimum run compared with the base run. This would suggest that, at an ideal rate, few households would be left as potential adopters of clean cookstoves by 2050. Besides, around 5.97 million and 6.62 million households in moderate and optimum runs, respectively, would switch to clean cookstoves. This would result in an increase of about 36% in the moderate run and a 50% increase in the optimum run. This is compared to the base run. This suggests that more urban households will transition to clean cooking than rural households. This phenomenon could be due to the relatively small household size in urban areas compared to rural areas. Furthermore, Figure 5.8 shows that fewer households are rejected than adopted. This suggests that the adoption rate supersedes the rejection rate at the end of the simulation year. Adoption and rejection rates suggest that, in the optimum run, the transition to clean cooking leveraged smaller household sizes, favourably informing decisions that support clean cooking adoption.

Scenario 3 (S3): For the price scenario, Figure 5.8 shows the impact of LPG prices on clean cookstove adoption. Around 1.35 million and 662 thousand households are yet to switch to clean cooking. This means that about a 49% decrease and a 49% decrease in the moderate and optimum runs are observed compared to the base run. This means fewer households will be left as potential adopters, although a similar trend is observed among all runs. Besides, around 5.68 million and 6.37 million households in the moderate and optimal scenarios,

respectively, would adopt clean cooking. Price change impacts adoption showing close relationships with rural households' adoption trends. The price scenario indicates that more urban and rural households will switch to clean cookstoves slowly at a lower LPG price. However, in the optimum run, the adoption rate of around 8.98 thousand and 12.20 thousand households per year in urban and rural households shows that the impact of changes in LPG price on adoption will be more pronounced among rural households. These changes suggest that more rural households will be willing to switch to clean cookstoves at a lower LPG price per kg than metropolitan households. This is at about a 36% adoption rate.

Scenario 4 (S4): In this scenario, around 1.27 million and 782 thousand households in the moderate and optimum runs, respectively, would be left as potential adopters at the end of the simulated year. These represent a decrease of about 52% in the moderate run and a reduction of about 70% in the optimum run. This is compared to the base run. The implication is that few households would adopt clean cookstoves in the optimum run. Potential adopters across all scenarios follow relatively similar trends, with different adoption values. Also, around 5.76 million and 6.25 million households would have adopted clean cookstoves, which means an increase of about 31% in the moderate run and an increase of about 42% in the optimum run compared to the base run would become adopters of clean cookstoves by 2050. The results suggest that information flow is relevant for cleaner cookstove adoption.

In addition, adoption rate results show that rural householders are affected more than urban households. This comparison shows a discrepancy of about 33% per year among rural and urban household adopters regarding the number of households reached. Outcomes from S4 on contact rate suggest that more households would have adopted clean cookstoves during the mid-year of transitioning. This would leave very few households to adopt or reject at the end of the simulation year. This shows that more households would have shifted to clean cooking before the end of the simulation year (2050). Urban rejection and rural rejection rates indicate that adopters in rural households will not reject clean cooking as soon as they spread the word via word-of-mouth. Analysis of the scenario of contact rate shows that the shift to clean cooking will increase among households with effective communication among potential adopters and adopters.

The results also reveal other significant insights. First, all related scenarios show similar trends. Second, price changes show slight divergence across trends. Third, more households adopt clean cookstoves than reject them, i.e., returning to their status as potential adopters.

Fourth, the flat trends observed at the beginning of the simulated year suggest that clean cooking adoption was slow, but not completely nonexistent. Adoption processes will be on throughout the simulation period, while adoption takes an S-shaped behaviour. The S-shaped behaviour observed across the study outcomes on clean cookstove adoption manifests the Bass model's adaptability to clean cooking transition dynamics.

While systematic review of literature by Lewis and pattanayak on the adoption of improved cookstoves by households in developing countries revealed that the influence of fuel availability and prices, household size and gender on clean cook-stoves are unclear (Lewis & Pattanayak, 2012). Hence, the current study does not only reveal a clear and quantitative impact of household size, income, fuel price, and contact rate on clean cooking adoption among rural and urban households, but it also reveals the dynamics of their impacts.

5.4. Discussions

The scenario analysis findings show that an increase in urban household income results in faster growth of clean cookstove adopters from 2017 at 448 thousand households. This peak is expected to reach 6.24 million in 2024. In contrast, the increase in rural household income translates into sharp growth among rural household adopters in 2028. This is with 8.71 million and 1.24 million households still belonging to the potential 'adopters' group. The speed of adoption in urban areas compared to rural locations implies that as consumers' socio-economic status improves, urban consumers are quicker to switch to cleaner technologies than rural dwellers. The slow and low adoption in rural areas might be attributed to several factors such as imitation effects, availability of clean cookstoves, and awareness. These factors can reinforce consumer resistance to upcoming technology. However, more adopters from rural households are likely to emerge in 2043 (Figure 5.6), which would surpass adopters from urban households. This could be a result of the adverse impacts of traditional stoves' continuous use and urban population growth and thus serve as a driver to adopt clean cookstoves in the future. In urban areas, the imitation effect is higher as most houses are situated close to each other with frequent interactions among neighbours (Chester, 2013; Haggstrom *et al.*, 2019; Shabanpour *et al.*, 2018). In the theoretical model shown in Figure 5.3, household income, which falls under economic factors, is an element of the sustainability theory that drives domestic demand for clean cookstoves. The availability of clean cookstoves in urban areas and scarcity in rural areas result in a critical infrastructure challenge that impacts household energy use. Here, infrastructure availability in the urban regions feed into the economic aspect connected to the social element via domestic demand. Therefore, households' economic power to adopt clean

cookstoves is lower in rural areas than in urban locations, as other non-financial factors come into play.

The change in household size also mirrors the outcomes of the S1 in both urban and rural areas. While this is surprising, the decrease in household size can free up disposable income for households to purchase new technologies after a period of high spending. For example, as children get older and move out of their parent's house, the homeowner would have more income to spend on newer fuels or technologies that can save the household cost in the long run (Chester, 2013). Price has a role to play in clean cookstove adoption. Our results show that reducing the price of LPG over the modelling period increases the adoption rate among households in urban areas compared to rural areas. Here, lower LPG prices alone might not encourage an increase in adoption. Other factors such as location and proximity to refueling stations or LPG refilling shops may be associated with a higher household adoption rate in urban locations than in rural areas (Pye et al., 2020). Lowering the price of LPG as a policy to incentivize a higher adoption rate may not achieve the desired goal if rural consumers have no access to refilling stations or shops. Therefore, they might not be motivated to switch technologies if support systems are not in place. The model shown in Figure 5.3 shows changes in family size are assumed to drive the increased supply. Simultaneously, the reduction in fuel cost (i.e., LPG) is expected to boost domestic demand and potentially increase the urbanization rate.

As earlier noted, spreading information via word-of-mouth or imitation effect plays a role in technology adoption, especially clean cookstoves. Our model results show that the contact rate to adopt clean cookstoves increased by 42% among urban households. At the same time, 6.25 million households were observed by the end of the simulation period. Spreading the word about improved cooking stove technology might have more impact in rural areas where most households know each other. However, this might not always turn out to be the case. The topic of discussion among rural consumers might not be how to save cost by using newer technologies if they are low-income earners or have challenges accessing the technology or refilling their tanks, as in the case of LPG stoves. Therefore, urban households tend to have higher adoption than rural consumers as it relates negatively to availability and positively to affordability, as observed in the literature (Bisu *et al.*, 2016). Availability is a significant barrier to enable cookstoves adoption. While affordability is necessary for market penetration, public engagement is vital (Price, 2017) Word-of-mouth, lower LPG prices and higher income alone might not improve the adoption of clean cookstoves in rural areas if the remote communities

lack LPG availability to meet demand. On the other hand, suppliers might find it counter-productive to deliver LPG to retail outlets in rural areas if there are poor access roads. This implies that the results align with our earlier assumption presented in the clean cooking transition management model shown in Figure 5.3.

This study suggests that policy impact differs by location, with little impact expected in rural areas than in urban locations. This is because consumers' response to market stimuli (such as price policies) and other stimuli (e.g., favourable socio-economic policies) differs across geographical locations. As earlier stated, reaching consumers in rural areas might be considered challenging for sellers of clean cookstoves who may want to balance high logistic costs with marketing costs. However, making clean cookstoves available to rural consumers creates an opportunity to reach a niche market with potentially large customers with fewer competitors than in urban locations (Vigolo *et al.*, 2018). To increase the revenue of sales in regional areas, a high number of sales must be achieved. Government can intervene in this case by providing access roads or introducing policies that encourage the distribution of clean cookstoves to rural areas (Puzzolo *et al.*, 2019; Quinn *et al.*, 2018).

Manufacturers of clean cookstoves could introduce marketing strategies such as bundling clean cookstoves with other technologies or services that might induce consumers to take up the technology (Shankar *et al.*, 2014). Specific examples include after-sales support and a guaranteed supply of gas refills at a fixed price for a given period. This approach can increase consumer value and improve the adoption experience with clean cookstoves. On the other hand, policymakers can increase community outreach programs in rural areas to raise awareness of the technology (Calzada & Sanz, 2018). This can alter consumers' perceptions and encourage them to switch their traditional stoves with more efficient and sustainable clean cookstoves. This should be done in collaboration with community heads while recognizing the role of women who are the primary users of stoves in Nigeria (Onyeneke *et al.*, 2019).

5.5. Conclusions and Policy Implication

Access to clean cooking energy systems in Sub-Saharan Africa is relatively poor compared to other regions. This study examines the influence of various strategies towards improving clean cooking energy adoption using Nigeria as a case study. It does so through the lens of system dynamics. The overarching finding is that the transition to clean cooking energy systems fluctuates and presents a non-linear trend over time. The study also found that these non-linear trends vary between rural and urban households. Scenario analyses showed that if income levels are not increased, reducing LPG prices alone will have little effect on potential adopters of clean cooking. Furthermore, households with smaller members can transition faster to clean cooking options than larger households. Therefore, the study infers that one policy strategy is insufficient to promote clean cooking in Nigeria's heterogeneous society.

Prioritizing dedicated policies and strategies will accelerate the transition to clean cookstoves. First, enhancing consumer demand by creating awareness, community engagement, and capacity building in local communities is critical to improving demand for clean cookstoves. Nigerian rural households are accustomed to firewood and convincing them to shift to cleaner fuels might be challenging. Preferences for traditional fuels might be due to an age-long tradition, while educating the public on the health and economic benefits can motivate consumers to switch to cleaner fuels for cooking. In this case, information channels, such as radio broadcasts, word of mouth, street plays, and rural social marketing at village gatherings, are often effective.

Second, addressing distribution and logistics challenges increases consumer demand for clean cooking by providing access to clean cookstoves and LPG in their communities. If the vendors are members of their community, the locals may have more confidence in the updated technology, as the vendors may also serve as repair technicians. Also, access to clean fuels in rural areas is paramount to increasing consumer adoption. Therefore, it is vital to develop local skill capacity and encourage partnerships with marketers to supply LPG to outlets in regional areas.

Third, lower LPG and clean cookstove prices mostly favor urban households (based on our model) over rural dwellers. There is a need to bridge the gap through finance mechanisms through outlets such as microfinance banks, credit unions, carbon finance, and cooperatives. In addition, there are direct government subsidies. The registration process for these credit facilities should be streamlined to ensure households gain access to a clean cookstove easily.

Fourth, policymakers should ensure vulnerable people who constitute the majority of rural households are not left behind in the race to decarbonize the household sector. In conflict zones and off-grid locations in Nigeria, disenfranchised members of the community suffer the most and are often left out of the policy debate. Although donor agencies have played a significant role in meeting the needs of those affected by the humanitarian crisis, the Nigerian government should build synergies with manufacturers to produce clean cookstoves at a quick scale to meet the basic needs of vulnerable households. This will reduce the unit cost and increase the adoption rate in the short term. In addition, Nigerian households will gradually decarbonize over the years.

Finally, given the dynamics surrounding the clean cooking energy transition, we recommend that various governments and other development agencies employ a multi-sectoral approach to improving clean cooking energy access. Public and private stakeholders, including but not limited to decision-makers, executors, and funders, should incorporate clean cooking energy goals into local and international development agendas. Furthermore, all policy frameworks need to consider consumers to ensure that all solutions are in tandem with consumers' social, cultural, and gender needs.

The current analysis is not without caveats. First, the study used only LPG to represent other modern clean cooking sources. While LPG is a clean cooking fuel, it is important to remember that it is also a fossil fuel. Consequently, future studies could explore the potential of other clean and climate-friendly cooking energy sources. Second, current study explored the influence of household income, house size, price per kg of LPG, and contact rate on adopting clean cooking in Nigeria. In reality, other factors (e.g., educational level, gender of household head, geographic location, and industrialization) can also influence clean cooking adoption. The other factors not considered, implies that there is room for further analysis of this subject matter. Third, due to the scarcity of Nigeria-specific data, the numerical results presented here should not be taken as exact values, but as average expected values. The modeled average values are relevant because modeling results are intended to be more directional and provide a broad quantitative sense rather than precise forecasts. While acknowledging these limitations, our analysis has shown the overall dynamics surrounding the transition to clean cooking in Nigeria and beyond. Overall outcome from this chapter, therefore, complements the existing evidence base for policymaking on the study's inquiry subject matter.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the study by constructively establishing its research framework and drawing relevant insights for planning the net-zero emissions strategies, as developing countries transition to clean energy. To do this, the current chapter synergises the divergence and contrast between outcomes from the analysis stakeholder's perspective and scenarios modelling based on OSeMOSYS, OEMOF, and systems dynamics framework. Also, relevant policy briefs, recommendations and further perspectives are proposed.

6.1. Conclusion

Countries must design a strategic planning route for their low-carbon energy development to strengthen government efforts towards limiting the average global temperature increase from reaching 1.5 °C above pre-industrial levels and well below 2 degrees Celsius.⁴³ There exist strategic plans that have translated into realistic low-carbon development efforts in developed countries, while their counterparts are still struggling to yield a holistic strategy to plan their clean energy paradigm. In the light of developing a strategic clean energy framework, several low-carbon strategies have been legislated, but implementation has faced several resistances. The impact of the latter resistance to ensure energy security is yet realized in most developing countries, especially in Sub-Saharan countries. The low impact experienced after implementing climate goals implies that achieving a clear low-carbon pathway that ensures a clean energy paradigm in developing countries is indeed complex. The complex nature of planning a clean paradigm in a developing country's energy sector is due to several factors, including social, economic, and technical. Exacerbating the challenge of meeting the demand of a large energy deficit and doing so with clean energy sources is huge, and achieving it is beneficial. The need to achieve the dual task embedded in energy security –meeting a large demand gap with sustainable and clean energy sources– has made planning energy transition in developing countries not only a complex and dynamic process but also a difficult one. It is, therefore, imperative to investigate how a sustainable energy transition that includes developing a low-carbon energy system and a net-zero emissions paradigm could be achieved and enhances the region's

⁴³<https://www.ipcc.ch/sr15/chapter/chapter-2/>

Energy Security Framework.⁴⁴ This study, therefore, explores the dynamics of low-carbon energy transitions and net-zero emission plans for developing countries, considering the Nigerian energy system perspective.

The analysis from the stakeholder's perspective assessment has suggested three thematic areas: clean technology and behaviour, energy finance bill, and clean advocacy. These thematic areas would need to be holistically investigated to support a sustainable and strategic energy transition and plan a net-zero emissions agenda in a developing country.

In addition, considering other sources of energy in the country's energy mix is crucial for enhancing the reliability of energy supply from the central utility and also ensuring deliberate investment in distributed clean energy. Investment in distributed generation, especially in solar energy technologies in the form of mini-grid systems that support energy security and the attainment of climate goals is crucial to achieving sustainable energy transition. Further, an open-source optimization tool, based on the bottom-up approach, is used to investigate the quantitative aspect of the stakeholders' perspective and validate the outcomes from the OSeMOSYS model. Finally, the study considers and explores clean cooking as one of the key drivers of the transition plan. The Nigerian energy sector was used as a standard for a typical developing country's energy context.

A summary of the main points

There is a need for low-carbon energy development in developing countries' energy sectors. Finance and investment, technology development, energy use, and behavioural patterns have been identified by stakeholders as the main thematic attributes and leverage points for action to achieve a holistic energy transition in Nigeria. On this premise, the main points from the study's outcome are presented based on the following research framework: the dynamics of stakeholders on energy transitions, distributed energy systems and energy efficiency, suitability of open-sourced models, and clean cooking in the transition framework.

The insight gained from the analysis of the stakeholders revealed that it is feasible to achieve a low-carbon development in Nigeria if appropriate financing tools, technology development, distributed energy systems, energy efficiency, conservation, and advocacy are legislated and enforced.

⁴⁴ Energy security means the ability of a person or household to have access to reliable and affordable both clean cooking facilities and electricity to meet their basic needs and enables productive economic activity (<https://www.iea.org/articles/defining-energy-access-2020-methodology>)

Further, to quantitatively model outcomes obtained from the stakeholders' analysis into a policy perspective, open-sourced energy modeling tools, such as OSeMOSYS, OEMOF, and PYPISA were identified. The identified modeling tools were proven to be compatible with the energy framework of DCs and showed their suitability by modeling thematic attributes that inform energy policy in the region. Also, the suitability assessment of the open-source tools revealed that DCs can become independent and own their energy transition modeling experience.

On the one hand, the application of the OSeMOSYS modeling tool on the Nigerian energy sector revealed that investment in solar energy should be prioritized owing to the recent reduction in the cost of solar energy technologies, especially solar Photovoltaics. This application would help in gaining relevance in the energy transition and subsequently net-zero emissions in the power sector. On the demand side, energy efficiency would play a significant role in the transition agenda, both in ensuring the security of energy by saving up to about 19,000 PJ of energy by 2050 and abating about 11.42% of CO₂ emissions in the power sector. In financial terms, up to 3.1 Trillion USD would be saved when the most efficient appliances are used.

On the other hand, the OEMOF application revealed a large energy demand deficit in the Nigerian Power Sector and shows how a distributed energy system framework would help ameliorate the energy deficiency in the NPS. The use of diesel-powered generators to meet captive demand can be gradually replaced by clean energy from renewable energy and subsequently solar energy in the future to achieve the net-zero emissions framework. In addition, in efforts to achieve the net-zero emissions target, natural gas will serve as a transition fuel. Hence, NG remains a significant fuel source for the short and medium-term, while solar energy technologies would serve as the most accepted and relevant future driver of the technology mix.

Further, green hydrogen fuel-cell technologies would extensively support the Nigerian green initiative to achieve net-zero emissions. Thus, electricity for the green initiative would be largely supplied by a purposeful and deliberate investment in solar technology. Moreover, to achieve a widespread utilization of solar energy technology in Nigeria, a distributed generation system is recommended through investing in a mini-grid to micro-grid. As a result, embracing electricity transmission among distribution companies (DisCos) would further enhance energy decentralization through a distributed generation strategy, as well as help control excess electricity that would otherwise be wasted or lost.

In the energy transitions context, clean cook also plays a significant role in attaining the climate goals, because the transition to clean cooking in the energy transition paradigm for most developing countries fluctuates and presents a non-linear trend over time a system dynamics

model approach is employed. In this regard, the study revealed that non-linear trends vary between rural and urban households, as they are likely to attain clean cooking at different future time scales. Among several factors that influence clean cook in low-income households, the price of clean fuel and household size are relevant. This relevance suggests that if income levels are not increased, reducing LPG prices alone will have little to no effect on potential adopters of clean cooking. Furthermore, households with smaller members can transition faster to clean cooking options than larger households. Therefore, the study infers that one policy strategy would not be enough to promote clean cooking in Nigeria's heterogeneous society.

A synopsis

The synopsis of this study presents a framework that would support government policy, investors, and relevant stakeholders by providing relevant insights on energy transition and how the net-zero emissions agenda could play a thematic role in the framework. Investigate the view of the relevant actors, requires a participatory and exploratory assessment of stakeholders' opinions and also conducts a suitability assessment of open-source energy models. And also, translating outcomes from the stakeholders' analysis and perception of net-zero emissions into modeling assumptions and also investigating the adoption of clean cooking considering natural gas a transition fuel would enhance the clean energy framework.

Based on the outcomes of this study, a call to action in line with the aforementioned objectives is formulated. These outcomes are listed as follows:

- i. All stakeholders in the energy sector – consumers, decision-makers, and investors – should be involved in the process of policy formulation, especially in the energy transition development framework towards the Nigerian net-zero emissions ambition to achieve its climate goals
- ii. Clean energy policy insight should be partly driven by participatory and explorative assessments from relevant stakeholders to inform the modeling processes of energy transitions. Thus, this insight may serve as a guide for a net-zero emission paradigm.
- iii. The U4RIA guidelines on the transparency energy system modeling are significant attributes that should be prioritized in clean energy analysis process. Moreover, some revealed open-source energy models offer such qualities. Aside from these qualities, DC would be able to use their *local* energy modelers to develop a strategic clean energy master plan. Therefore, energy policy modeling processes are more meaningful when performed at a local or regional level – modeling by local modelers from an international perspective

- iv. Solar energy technologies, energy-efficient appliances, consumers' behavior (towards energy conservation), clean energy incentives, clean cooking, distributed electricity, natural gas as a transition fuel, and hydrogen and fuel cell technology should be critically considered in the development of a clean energy framework
- v. The net-zero emissions paradigm offers reliable pathways to both decarbonize the energy sector and assure energy security through a critical review of item four (4.).
- vi. The heating and cooking sector is often one of the most difficult sectors to decarbonize in most DC due to low electricity per capita. Considering a cooking fuel such as LPG could help support decarbonizing this sector in the short and medium term by incentivizing the product and adopting proper advocacy.

6.1.1. Key messages

The thesis has scientifically addressed and answered the research questions raised in Chapter one.

First, stakeholders' views have identified solar energy technologies (for mini-grid, SHS), clean energy incentives (such as tax holidays and low-interest rates on clean energy, easy access to loans), and other financial tools as future clean energy drivers. Also, energy efficiency, consumer behavior, clean-energy advocacy, and research & development are relevant policy tools that could enhance the energy security of clean energy transition towards achieving climate goals in the short-mid and long term.

Second, open-source energy models have been investigated and proven to capture relevant characteristics that delineate developing countries' energy structures and policy interests.

Third, open-source models and system dynamics have translated modeling assumptions based on information obtained from the stakeholder perspective. As stated earlier, solar energy technologies, energy efficiency, and distributed energy generation have been identified as the policy instruments that would not only support universal access to clean energy in the form of electricity and cooking but also enhance net-zero emissions targets.

6.2. Recommendations

This section succinctly discusses ways to help solve problems discovered in the thesis. It calls to either continue a good system of practice or revamp all the areas in need of improvement. Hence, the study has identified the following recommendations:

- i. Policymakers should consider a robust representative sample of stakeholders in the energy sector before and during the process of legislating and implementing clean energy transition policies;
- ii. Researchers and energy modelers should embrace the uniqueness of transparency embedded in open-source energy modeling tools. Also, they should consider the U4RIA guidelines when developing energy models in both the modeling framework and methodology to encourage or inform a transfer of energy modeling techniques and best modeling practices to emerging economies;
- iii. Although solar energy has gained attention from the Nigerian government, for rural electrification (REA, 2018), underserved communities, and boast the merger electricity supplied to some institutions of learning, there is a need for more investors in the solar energy sector to invest in solar home systems and government should critically embrace investing in energy-efficient appliances
- iv. Legislators and the executive arm of government should revisit the energy efficiency framework for efficient appliances, and energy-consumer behavior (conservation) across all relevant energy demand sectors. Also, necessary incentives and adequate legislation and implementation should be considered to support energy users;
- v. Clean-energy advocacy by the relevant media houses, agencies, and Non- Governmental Organizations (NGOs) with support from the government for solar energy technologies, especially, the use of energy-efficient appliances and behavior should be facilitated and mainstreamed.
- vi. The managers and executives of distribution companies (DISCOs) should embrace distributed energy generation among other DISCOs. This ... could enhance curtailing wastage in the power distribution;
- vii. Government and other development agencies should employ a multi-sectoral approach to improving clean cooking energy access among rural and urban households.

6.2.1. Perspectives

Consider another sector in the dynamics, such as transport by investigating with a scenario-based assessment of various prices of premium motor spirit, which is the main fuel in most

developing countries.

Consider conducting the same modeling analysis with PYPASA, since it is one of the most valuable open-source modeling energy tools according to the suitability assessment tools in Chapter three. Further, an assessment of the dynamics of decarbonization towards net-zero emissions in the industrial sector by considering the role of hydrogen fuel-cell technology is a relevant future work.

Future studies should consider solar energy technology and energy-efficient appliances that would encourage further penetration of clean energy technologies. The penetration of clean energy shall enhance lighting and could help ameliorate the insecurity situation, in the form of solar-powered street lighting facilities and community camera sensors, respectively. Also, the impact of climate change on the energy system should be investigated in future studies. The impact would include using climate models such as a coupled model intercomparison project, and the Shared Socio-economic Pathways (SSPs) to further gain insight into the present and future energy planning framework.

In addition, the system dynamics modeling approach strategically investigates qualitative and systematic assessments of stakeholders and clean energy transitions. Due to the nonlinear behavior and complex attributes of the leverage points (such as financial incentives, the role of energy efficiency, and solar energy, etc.) identified in Chapter one, the system dynamics modeling paradigm is suitable to provide further insights that guide decision-makers and investors' decisions for the energy transition of a typical developing country context. Investigating the role of the variables, as complex systems over time and drivers of clean energy transitions using SD, is, therefore, a potential future study area.

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APPENDICES

Appendix A

Publications from Thesis

- Shari, B. E., Dioha, M. O., Abraham-dukuma, M. C., & Sobanke, V. O. (2022). Clean cooking energy transition in Nigeria : Policy implications for Developing countries. *Journal of Policy Modeling*, *xxxx*, 1–25. <https://doi.org/10.1016/j.jpolmod.2022.03.004>
- Shari, B. E., Madougou, S., Ohunakin, O. S., Blechinger, P., Moumouni, Y., Ahmed, A., & Tukur, Y. (2023). Exploring the dynamics of stakeholders' perspectives towards planning low-carbon energy transitions: a case of the Nigerian power sector. *International Journal of Sustainable Energy*, *42*(1), 209–235. <https://doi.org/10.1080/14786451.2023.2186147>
- Shari, B. E., Moumouni, Y., Ohunakin, O. S., Blechinger, P., & Madougou, S. (2024). Exploring the role of green hydrogen for distributed energy access planning towards net-zero emissions in Nigeria. *Sustainable Energy Research*, *11*(16), 1–23. <https://doi.org/10.1186/s40807-024-00107-1>
- Babajide E. Shari, Moumouni Yacouba, Ohunakin S. Olayinka, Saidou Madougou, Philipp Blechinger, Nnenna C. Nwankwo, Mashinini Madindwa, Victor Aladesanmi (2025). Open-Source Tools for Modelling Energy Transitions Paradigm in Developing Countries: A Compatibility Assessment Study. *Discover Sustainability*, Springer Nature. Manuscript ID: 3252a890-5cc1-4a87-8178-aab8a12e56ac v1.0 [**Under pair-review**]

Appendix B

Stakeholder Interview, for qualitative data

A. Interview guide

1. Introduction

Introduction of research project and researcher

Ask for permission to record

B. Interview questions

II. Personal Experience

1. Could you briefly introduce yourself?
2. Could you tell us about your professional background of the last ten years of working within the Nigerian energy sector?
3. Are you aware of the concept of energy transition as a significant structural shift in an energy sector from fossil-fuel based system of energy production to renewable energy sources?
4. How does your current position relate to the advancement of Energy transition in Nigeria?
5. What is your vision on the energy transition from the perspective of your profession?
6. How important is energy transition according to you as a person, and from the perspective of your profession?
7. What is your strategy for the implementation of clean energy transition throughout Nigeria?

III. Energy transition and its concerns

8. In addition to all the various urgent needs/demands/objectives such as economic growth, COVID-19 number of cases reduction, agrobusiness etc., Where will you place energy transition relative to other needs, Also, if choices must be made, where would the attention go to (with regard to other themes)?
9. Nigeria is capable of achieving 100% clean energy transition by 2063 by considering current trends in the economy growth and the power sector reform?
10. Is Energy transition important or needed for sustainable development? If yes, give reason(s)? If NO, what would have to change to make this important?

11. What is most crucial to achieving energy transition in the Nigerian power sector by 2050?
12. What are the biggest challenges in the energy transition (think of mobility, infrastructure and greening the power sector, among others)?
13. What are the biggest challenges mitigating against energy transition in the Nigerian power sector?
14. Kindly proffer some effective solution(s) that are most relevant to achieve the successful energy transition in the NPS
15. To what extent does the affordability of an alternative energy solution contribute to the choice to become more sustainable, according to you?
16. In view of 2030, how do you see the feasibility of energy transition in 2030 compared to now (What should change to speed up things)?
17. What would cooperation between the state, local government, your organization and other stakeholders mean as a driving force to achieving a cleaner power sector?
18. What would a successful energy transition in the NPS mean for the Nigerian economic growth?
19. How do you see the role of the citizen (i.e., consumer) in energy transition and when should citizens be involved in the process?
20. Would electric grid run 100% renewable energy in the future?
21. In the future, would all Nigerian citizens and businesses be generating their own electricity
22. What do you think are common interests among stakeholders in the energy transition and are there options for aligning them? what is therefore needed within now and the next5 years?

III. Financing and economies of energy transition

23. Are additional incentives needed in order to make RE more cost-competitive?
24. What financial innovation (i.e., taxes, rebates) is/are required in energy provision to achieve needed energy transition in Nigeria power sector?
25. How do you think current conditions in the Nigerian banking systems could enhance the needed finance for the realization of energy transition in the power sector?
26. Do you think the country is giving energy transition in the power sector enough attention and consideration in her annual budget? Yes No

27. If no, what are the likely suggestions on how government can give more attention to energy transition and consideration in its national budget?
28. What significant role would Feed-in tariff play in achieving low-carbon/clean energy transition?
29. In your own opinion will economic growth accelerate the transition to low-carbon economy?
30. Will a low-carbon economy mean less energy and material consumption?
31. Economic growth should be balanced with environmental and social impact
32. The RE transition will improve the prosperity and well-being of all Nigeria
33. Do you have any comments/suggestions/recommendations that I should include in my research on stakeholders in the energy transition?

Thank you for your attention!!!!

Appendix C

Nigerian low-carbon energy transitions Survey

Assessing stakeholder preferences on integrated energy planning towards low-carbon transitions

Objective of the survey

This survey aims to collect data on stakeholder engagement, views, drivers, participation and practices to evaluate the dynamics of low-carbon transitions and its perspectives among stakeholders in the Nigerian power sector. The objective is to provide evidence-based assessment of the main drivers and views of stakeholder engagement in Nigeria low-carbon transitions policy and projects, identify best practices, and to provide policy recommendations. Also, to scale-up good practices that will support energy planning that integrate a low-carbon approach in an energy transitioning perspective.

Target audience for the survey

The survey targets approximately 200 major stakeholders in the Nigerian power sector including governments (federal, state, local), service providers (public, private and mixed), financial actors, civil society organisations (CSO), academia, consumer associations, research and training institutes, regulators and advisors.

Consequently, this survey requires respondents to share their experience - in energy transition and planning in the Nigerian power sector.

Respondents to the survey are kindly requested to:

1. Provide their contact details for follow-up in case clarification are needed;
2. Answer as many questions as possible on behalf of your organisation
3. Provide links/references to background documents and websites where relevant;

Organisation	
Position	
Phone number/E-mail	

Respondents are informed that:

1. Responses are confidential and will only be treated quantitatively and qualitatively for the analysis; respondents and their organization will not be quoted directly in the final study;
2. Addressing thoroughly all the questions requires roughly 20mins but comprehensive responses will be extremely valuable to the analysis;
3. Instructions written in *italics*

QUESTIONNAIRE

1. Mapping stakeholders and their core motivations

This section aims to identify stakeholder affiliations, engagement and their core motivations.

a. Select the appropriate organization you belong as related to the Nigerian power sector

Please, tick **ONLY** one box and specify when need be.

Inter-government	<input type="checkbox"/>
Government	
National/Federal (ministry, public, agency)	<input type="checkbox"/>
Regional/State	<input type="checkbox"/>
Local	<input type="checkbox"/>
Service provider	
Public utility	<input type="checkbox"/>
Private operator	<input type="checkbox"/>
Public-private partnerships – PPP	<input type="checkbox"/>
Associations/Networks	<input type="checkbox"/>
Regulator	
Economic	<input type="checkbox"/>
Environment	<input type="checkbox"/>
Financial Actors	
Donor	<input type="checkbox"/>
Financial institution	<input type="checkbox"/>
Investor	<input type="checkbox"/>
Science, academia and research institute	<input type="checkbox"/>
Consumer association	
Organised domestic power users	<input type="checkbox"/>
Trade unions and workers	<input type="checkbox"/>
Advisors	
Engineering – consulting firms	<input type="checkbox"/>
Civil society	
Non-governmental organization	<input type="checkbox"/>
Social movement	<input type="checkbox"/>
Community based organisation	<input type="checkbox"/>
Media	<input type="checkbox"/>
Other, please state	

b. What are your organisation's primary areas of interest in the power sector?

Please rank from 1 to 7, starting with the most important area of interest (1) to the least important one (7)

Area of interest	rank
National policy and planning	
Investment and finance	
Supply and electrification	
System operator	
Transmission and Distribution	
Market operator	

Research and development	
--------------------------	--

c. At which territorial scale does your organisation primarily intervene in power issues?

Please tick as many as applicable to your organization

Territorial scale	Tick
International level	
National/Federal level	
Regional/Geopolitical level	
State level	
Municipal/Local government level	
Community/Neighborhood level	

2. Objectives and stages of organization involvement in energy planning and energy transition

This section aims to understand the reasons why different groups of stakeholders are engaged in energy related decision-making and when (at which stage of a project or reform).

d. Does your organization's core value support "low-carbon/clean energy transition"?

Yes No

e. Has your organization been involved in clean energy projects? Yes No

f. If yes, kindly tick the type of clean energy project carried out in your organization

Please tick as many as applicable to your organization

Clean energy projects	Tick
Investment and advocacy on clean cookstoves	
Investment in innovative renewable energy	
Advocacy on renewable energy and energy efficiency	
Research and development in clean energy projects	
Others, please state	

g. How does your organisation contribute to better planning in the power sector?

Please tick a Yes or No as many as applicable to your organization

Objectives	Yes	No
Supporting effective implementation of a policy, reform or project		
Ensuring proper enforcement of regulations and norms		
Raising awareness on clean energy transitions project		
Building/Operating/Maintaining low-carbon energy infrastructure		
Ensuring value for money (i.e., better quality of services/resources at lower costs)		
Increasing the willingness to pay of energy users		
Contributing to the financial sustainability of energy planning and low-carbon transitions/clean energy transition		
Fostering capacity building, qualifications, training in low-carbon energy		
Providing funds for investment in clean energy transition in the power sector		

Sharing information on issues and process of interest to stakeholders		
Fostering corporate social responsibility and codes of conduct respect		
Building trust and confidence		
Building political acceptability (for specific ownership models, delivery options, new technologies, etc.)		
Helping opinion forming and development of preferences		

h. At which stage of an energy-related project and/or reform does your organisation usually get involved?

Please tick as many as apply to your organization

Stage of development	Always or almost always	Often	Sometimes	Rarely	Never or very rarely
Early stages (conception, planning, design, feasibility studies)					
Development / Deliberation					
Funding/Finance					
Implementation / Operation					
Execution and communication					
Evaluation (including monitoring)					

3. Information about low-carbon /clean energy transitions

Please tick a Yes or No as many as applicable to your organization

Information about energy transition	Yes	No
Energy transition is a significant structural shift in an energy sector from fossil-fuel based system of energy production to renewable energy sources		
Are you aware of the concept of energy transition		
Has the Nigerian energy system undergone significant structural changes in its power sector in line with energy transition agenda?		
Have you been involved in energy transition training for the power sector?		
Have you managed/co-managed an energy transition projects?		
Is dependency on fossil fuel fading out gradually in the Nigeria energy space?		
Would you advocate that energy transition should be included in the academic curriculum?		
Do you know what is said in the Paris climate agreement?		

i. What is for you the most important task in energy transition?

Please rank from 1 to 5, (1) least task (5) most important task

Ranking scale

5	4	3	2	1
Most important	Important	Neutral	Not important	Least important

Task	Rank
Sustaining in every way possible	
More on the use of fossil fuel sources	
Making others aware of the importance of energy transition	
Gaining more Knowledge of the topic	
I don't have a task, it's not up to myself	

j. Indicate as in your own opinion

Please tick accordingly as it applies to you and/or your organization

	Strongly Agree	Agree	Neutral	Disagree	Strongly disagree
1) The energy transition is an important subject which should definitely get attention in my environment					
2) The energy transition doesn't bother me					
3) The government is the one that should take measurements against global warming, not the citizens of the Nigeria					
4) Transitioning to cleaner energy is possible solution to power supply-demand gap in Nigeria?					
5) Transition to cleaner energy bring about sustainable energy efficiency in the Nigerian power sector?					
6) Transition to cleaner energy bring about economic prosperity in the Nigeria power sector?					
7) A cost reflective tariff would bring about the needed clean energy transition in the future?					
8) Nigeria is capable of achieving 100% clean energy transition by 2063 by considering current trends in the economy growth					

and the power sector reform?					
9) Creating consumer awareness about energy efficiency could facilitate energy transition agenda and African Union Agenda 2063					
10) COVID-19 has slowed down the pace of achieving universal clean energy access in Nigeria?					
11) Power decentralization would play a significant role in enhancing energy transition					
12) Transitioning to clean cooking could enhance low-carbon transitions in the power sector					

k. Indicate per concept where you place them (in terms of importance), when it comes to energy transition:

Please tick accordingly as it applies to you and/or your organization

	Most important	Important	Neutral	Not important	Least important
Affordability					
Reliability					
Sustainability					
Feasibility					
Safety					
Decentralization (mini-grid, stand-alone systems)					
Central utility grid system					
Infrastructure					

4. Technology options and preferences

Here, stakeholders are asked about their preferences on technology options towards a low carbon future

l. Which technologies will be most important to achieve African Union agenda on energy access and clean transition by 2063?

Please rank from 1 to 5, (1) least task (5) most important technology

Ranking scale

5	4	3	2	1
Most important	Important	Neutral	Not important	Least important

Technology option	Rank
Solar	

Wind	
Hydropower (micro, mini, large)	
Carbon Capture and Storage	
Biomass	
Natural Gas	
Oil	
Coal	
Energy efficiency	
Storage	
Hydrogen	
Other (specify)	

m. Which should receive more public and government support?

Technology option	Rank
Solar	
Wind	
Hydropower (micro, mini, large)	
Carbon Capture and Storage	
Biomass	
Natural Gas	
Oil	
Coal	
Energy efficiency	
Storage	
Hydrogen	
Other (specify)	

n. With a view to climate change mitigation investments in the nations energy sector, which technologies, do you think, **WILL** be the most important during the next 30 years?

Technology option	Rank
Solar	
Wind	
Hydropower (micro, mini, large)	
Carbon Capture and Storage	
Biomass	
Natural Gas	
Oil	
Coal	
Energy efficiency	
Storage	
Hydrogen	
Other (specify)	

o. In your personal/professional opinion, how will the different technology options develop in the next 30 years at a national scale?

Please tick the options (technology will phase-out, unchanged or expand) where appropriate

Technology option	Expansion	Unchanged	Phase-out
Solar			
Wind			
Hydropower (micro, mini, large)			
Carbon Capture and Storage			
Biomass			
Natural Gas			
Oil			
Coal			
Other (specify)			

5. National energy transition and financial innovation

- p. Do you think the country is giving energy transition in the power sector enough attention and consideration in her annual budget? Yes No
- q. If no, what are the likely objective solutions to making energy transitions gain relevant attention?

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- r. What financial innovations are mostly appropriate to achieving 70% low-carbon transition by 2030? Please tick accordingly as it applies to you and/or your organization

	Most important	Important	Neutral	Not important	Least important
Tax holiday on renewable energy component (i.e., solar panels, batteries, wind turbines)					
Low interest loan rate by commercial bank to investors of clean energy					
Low tax rate on energy efficient components i.e., energy saving bulbs					
Available, easy to access grants for investors of clean energy					
Easy access to foreign exchange (FOREX) to investors in renewable energy sector					

- s. Select the most appropriate consideration to achieving a low-carbon energy transition by 2050

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
i. Finance has been the major bottle neck to achieving realistic low-carbon					

	transitions?					
ii.	Increase in price of fossil-fuel products (i.e., petrol, diesel) encourage energy transition in power sector?					
iii.	Low prices in renewable energy components enhance investment in energy transition					
iv.	Weak enabling environment could delay energy transitions?					
v.	Investing in research and development in clean energy be necessary in achieving needed low-carbon transition in the power sector?					
vi.	Full liberalization of the power sector encourages private investors					
vii.	The full engagement of private investors slow-down the process of energy transition in the power sector?					
viii.	Investing in energy research institutions is relevant to achieving the need low-carbon transition in the power sector					
ix.	Productive engagement between universities (academia) and industries could enhance energy security in the energy transition processes?					
x.	Incentives that encourage energy efficiency behaviour could expand clean energy users?					
xi.	Increase in electricity tariffs encourage low-carbon transition in the power sector					