OPTIMIZING THE NIGERIA ENERGY MIX FOR COST-EFFECTIVE AND SUSTAINABLE ENERGY GENERATION

A thesis submitted to the faculty at African University of Science and Technology

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in the Department of Petroleum and Energy Resources Engineering

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CERTIFICATION

This is to certify that the thesis titled "OPTIMIZING THE NIGERIA ENERGY MIX FOR COST-EFFECTIVE AND SUSTAINABLE ENERGY GENERATION" submitted to the school of postgraduate studies, African University of Science and Technology (AUST), Abuja, Nigeria for the award of the Masters degree is a record of original research carried out by BEATRICE EJEH in the Department of Petroleum and Energy Resources Engineering.

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By

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ABSTRACT

Nigeria, a nation endowed with diverse energy resources, faces a complex energy landscape characterized by historical reliance on fossil fuels, energy security challenges, and environmental concerns. Diversifying the energy mix is essential to balance the need for cost-effective electricity generation with the imperative of reducing greenhouse gas emissions.

This study aims to develop a comprehensive energy mix optimization model for Nigeria. The objectives are twofold: first, to minimize the total cost of electricity generation while maximizing energy security, and second, to reduce greenhouse gas emissions to meet international environmental commitments.

The research employs a quantitative approach, utilizing mathematical optimization techniques and scenario-based analysis. Decision variables are defined to represent the percentage allocation of gas, hydro, wind, and solar energy sources. The model integrates data on capacity, energy demand, cost per megawatt, and CO_2 *emissions to assess different energy mix scenarios. Scenario results are visualized using graphs and charts, enabling policymakers and stakeholders to make informed decisions.*

The study produces a range of optimized energy mix scenarios for Nigeria, considering total energy generation from 25GW to 200GW. These scenarios reflect the trade-offs between cost, renewable energy integration, and carbon emissions reduction. Sensitivity analysis is conducted to assess the robustness of the results.

The findings of this study have significant policy implications. They inform decisions related to energy planning, emissions reduction targets, and energy security. The study contributes to Nigeria's commitment to environmental sustainability and aligns with international efforts to combat climate change.

Optimizing Nigeria's energy mix is critical for economic stability, energy security, and environmental sustainability. This study provides a structured framework for addressing these challenges, offering practical solutions and policy recommendations that can guide the nation toward a brighter and more sustainable energy future.

The study's findings aim to strike a balance between economic efficiency and environmental responsibility, reflecting Nigeria's commitment to a sustainable and resilient energy sector.

Keywords: Energy mix, CO_2 ***emissions, sustainability, optimization, cost, power generation***

DEDICATION

I dedicate this thesis to God Almighty who gave me the strength and the knowledge needed for this course. I also dedicate it to my parents and my siblings who have been my pillar and have always encouraged me to be educated and be what I am academically today. In a special way, I dedicate this work to those out there seeking positive ways to solve Nigeria's power challenges and also finding ways to minimize climate change impacts the world over.

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I want to also thank my family who have been a great pillar and support. They are the reason why I pushed through to the end. I thank everyone who made my journey at AUST smooth and memorable. God bless you all.

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LIST OF ABBREVIATIONS AND ACRONYMS

AC	-	Africa Case
ESOM	-	Energy Systems Optimization Model
RE	-	Renewable Energy
LCOE	-	Levelized Cost of Energy
NEMOM	-	Nigeria Energy Mix Optimization Model
HES	-	Hybrid Energy Systems
RES	-	Renewable Energy Sources
TES	-	Total Energy Supply

CHAPTER 1: INTRODUCTION

1.0 INTRODUCTION

Since the 1970s, there has been a growing focus on developing more sustainable energy systems. In recent decades, this shift towards sustainability has gained momentum, propelled by technological advancements in areas like renewable energy, energy storage, carbon capture and storage, biofuels, and hydrogen.

Despite substantial progress globally, the adoption of diverse energy mix options as part of the energy transition presents significant technological, commercial, and political challenges for both businesses and governments.

According to Planete Energies (Planete Energies, 2023), the term "energy mix" refers to the combination of various primary energy sources used to fulfill energy needs in a specific geographic region. These primary sources encompass fossil fuels (oil, natural gas, and coal), nuclear energy, and various renewable sources (wood and other biofuel, hydro, wind, solar, and geothermal). Different sectors employ these sources for power generation, transportation, residential and industrial heating and cooling, among other applications.

The composition of the energy mix varies widely between countries or regions and can change significantly over time and under different conditions. Factors influencing the energy mix include the availability of usable resources, either domestically or through importation, the type and extent of energy needs (with a focus on the Power sector in this study), and policy choices influenced by historical, economic, social, demographic, environmental, and geopolitical factors.

Over the past decades, the energy mix has undergone changes, marked by a decrease in oil production, a similar but less pronounced trend in natural gas, a continued upward trajectory for renewables, and a reduction in nuclear and coal. These shifts are, in part, a response to efforts aimed at decarbonizing the energy system.

It's widely recognized that a power sector free from carbon emissions, primarily reliant on renewable sources, plays a pivotal role in moving towards a sustainable energy future. This research specifically delves into the composition of power generation and explores ways to optimize it for the Nigerian economy, ensuring a balance between cost-effectiveness and environmental sustainability.

Power Generation (Electricity) Mix:

The power generation (electricity) mix denotes the blend of energy sources employed for producing power in a specific geographical area. Globally, coal predominates in the electricity mix; however, recent trends indicate a substantial shift in the next few years, marked by a significant increase in the use of renewable energies and natural gas.

Differences in the power generation mix are evident among countries due to varying global markets, national policies, and local fuel production.

Electricity is indispensable for industry, buildings, and daily life, yet its generation relies on primary energy sources like coal, natural gas, uranium, the sun, wind, or water. The methods employed for electricity production also contribute significantly to global CO_2 emissions. Therefore, the choice of generation technology holds a crucial role in minimizing the environmental impact of electricity, especially given that coal, at one extreme, has a carbon footprint 20 times greater than renewables at the other extreme.

Despite being cost-effective and easily producible, coal currently serves as the primary fuel for global power generation, contributing to over 38% of the energy mix in 2018. However, the gap with natural gas (23.4%) is narrowing. While fuel is crucial for transportation and industry, its utilization for electricity generation is less common. Among renewables, hydro is the most prevalent, constituting nearly 16%, while wind (4.8%) and solar (2.2%) are steadily gaining momentum. Nuclear energy accounts for just over 10% (Ritchie, 2020).

Presently, 80% of power generation relies on gas, and the majority of the remainder comes from oil, with Nigeria leading in the use of oil-fired backup generators in Africa. Although natural gas remains the primary power source in the Africa Case (AC), there is a noticeable shift towards solar PV as the country begins to tap into its substantial solar potential (IEA, 2019).

1.1 BACKGROUND OF THE STUDY

Nigeria is the largest economy and the richest oil resource center of the African continent. The country also remains the largest gas consumer and producer of West Africa. Notable power sector reforms are underway in Nigeria, including plans for electrification, but limitations in the power sector constrain growth. Nigeria is endowed with large oil, gas, hydro and solar resources, and it has the potential to generate 16GW of electric power from existing plants. On most days, however, it is only able to dispatch around 4,000 MW, which is insufficient for a country of over 200 million people. The Nigerian power sector experiences many broad challenges related to electricity policy enforcement, regulatory uncertainty, gas supply, transmission system constraints, and major power sector planning shortfalls in addition to clean energy sustainability that have kept the sector from reaching commercial viability.

This project addresses this challenge by combining a detailed overview of the techno-economic aspects of the energy mix including gas and individual low carbon technologies (Solar, Hydro, Wind) with an understanding of energy systems and energy systems integration. Also, there might be a little dive into the non-technical aspects of the energy transition, such as the various economic and policy developments, without which many technologies would not develop beyond the laboratory.

1.2 JUSTIFICATION OF THE STUDY

Addressing the rising energy needs of expanding populations and emerging societies while diminishing reliance on fossil fuels poses pivotal challenges for the worldwide energy sector. Nigeria is no exception, grappling with these same challenges. As fossil fuels deplete progressively and climate change accelerates, the quest for alternative sources of clean energy has intensified significantly in recent times. Notably, options like wind, solar, biomass, and geothermal energy are experiencing remarkable advancements.

THE NEED FOR AN OPTIMIZATION MODEL

The International Energy Agency (IEA) reports that Nigeria is Africa's largest oil producer and has the largest proven gas reserves on the continent. However, it also faces difficulties in satisfying its domestic energy demands and providing reliable and affordable electricity to its population. Despite being Africa's most populous and wealthy nation, Nigeria's per capita electricity consumption is very low, only a very small fraction of what South Africans consume each year. Nigeria's power production is inadequate for its demand, which limits its economic growth, as it has only 16 GW of installed capacity and usually delivers only a third of that. But what is the size of the shortfall between the demand and supply? And what does future demand look like?

Answering concerns about our future energy demand and supply requires that we utilize theory, tools and models on the basis of which we imagine a vision of the future and formulate a strategy to establish the desired energy mix that is suitable for the anticipated future (Gruenwald, O., Oprea, D., 2012).

Modeling the power system with various energy mix alternatives is essential to achieve this goal. Optimization models have long been the backbone of energy systems modelling" as described by

(Pfenninger, S. et al, 2014). According to a recent study (Lopion P et al, 2018), optimization has been the most used methodology for energy system analysis since 2010. Energy Systems Optimization Models (ESOMs) are also robust models owing to the detailed techno-economic structure and the ability to analyze national policies (Burandt T. et al, 2019). In this sense, ESOMs are widely used to model the system impacts of energy transition (DeCarolis J. et al., 2017). ESOMs enable finding a least-cost energy system according to exogenous assumptions over a long-term time horizon or for a specific year depending on the setting of the model, providing the cost-optimal combination of fuels and conversion technologies to satisfy the energy demand (F.A. Plazas-Ni˜no et al, 2022). In addition, ESOMs can also operationalize the three central objectives of energy trilemma as follows: Affordability: Minimize total system costs; Environmental goals: Diminish total GHG emissions; and Energy security: Satisfaction of demand plus model-specific constraints (Weber J et al, 2019).

Developing an optimization model for the energy mix is a complex task due to numerous factors influencing the optimal energy combination and costs for Nigeria. These factors include:

- The availability and accessibility of diverse energy sources such as oil, gas, solar, hydro, and wind.
- The environmental and social impacts associated with different energy sources, encompassing aspects like greenhouse gas emissions, air pollution, land use, and water consumption.
- The technical and economic feasibility of various energy technologies, covering power generation, transmission, distribution, storage, and end-use efficiency.
- The policy and regulatory framework governing the energy sector, including factors like tariffs, subsidies, and taxes.
- The market dynamics and competition influencing the supply and demand of energy services, encompassing aspects like price, cost, revenues, profits, risks, and opportunities.

To optimize the energy mix in Nigeria, it is crucial to weigh the trade-offs and synergies among these factors and adopt a comprehensive and integrated approach that aligns with the objectives of energy security, economic development, social equity, and environmental sustainability. However, a more detailed and specific analysis is necessary to assess the potential impacts and outcomes of various scenarios and options, making the creation of an optimization model imperative.

1.3 PROBLEM STATEMENT

According to the International Renewable Energy Agency (IRENA), Nigeria's energy mix in 2020 was as follows:

- Renewable energy: 76% of total energy supply (TES), mainly from bioenergy (such as wood, charcoal, crop residues, and animal dung) used for cooking and heating.
- Non-renewable energy: 24% of TES, mainly from natural gas (15%) and oil (9%) used for power generation, transport, and industry.

Nigeria's energy mix has changed over the years, but not significantly. According to the International Energy Agency (IEA), Nigeria's energy mix in 2015 was as follows:

- Renewable energy: 77% of TES, mainly from bioenergy.
- Non-renewable energy: 23% of TES, mainly from natural gas (16%) and oil (7%).

The main changes in Nigeria's energy mix from 2015 to 2020 were:

- A slight decrease in the share of renewable energy, mainly due to the increase in the use of natural gas for power generation and industrial development.

- A slight increase in the share of non-renewable energy, mainly due to the increase in oil production and exports, as well as the use of oil-fired back-up generators to cope with frequent power outages.

However, these changes were not enough to diversify Nigeria's energy mix and reduce its dependence on fossil fuels. Nigeria still faces many challenges in its energy sector, such as low electricity access, high energy poverty, poor infrastructure, inefficient use of resources, and environmental impacts. To address these challenges, Nigeria needs to optimize its energy mix and cost implications by increasing its renewable energy share, improving its energy efficiency, and enhancing its energy security.

Decarbonization is happening, but not nearly fast enough. To achieve the necessary progress that matters for the climate, we need to see its growth meet not only our new energy demands each year, but start displacing existing fossil fuels in the energy mix at a much faster rate.

Nigeria is endowed with large oil, gas, hydro and solar resources, and it has the potential to generate 16 GW of electric power from existing plants. On most days, however, it is only able to dispatch around 4,000 MW, which is insufficient for a country of over 200 million people. The Nigerian power sector experiences many broad challenges related to electricity policy enforcement, regulatory uncertainty, gas supply, transmission system constraints, and major power sector planning shortfalls in addition to clean energy sustainability that have kept the sector from reaching commercial viability.

This project tackles the challenge by amalgamating a comprehensive examination of the techno-economic facets of individual Low Carbon Technologies (LCTs) such as Gas, Solar, Hydro, and Wind, with a comprehension of energy systems and their integration. Additionally, it delves into the non-technical dimensions of the energy transition, encompassing economic and policy developments, recognizing their pivotal role in advancing technologies beyond the laboratory stage.

Furthermore, this project delivers insights into both the evolving nature of energy systems and the technologies that will wield significance in the future. Global energy systems are currently undergoing transitions driven by factors like environmental impacts (particularly climate change and air quality concerns), escalating demand for universal and reliable energy access (as evidenced by the upward trend in energy consumption), and the challenges posed by increasing urbanization, which exerts pressure on infrastructure.

Therefore, the development of a system or model that addresses these challenges becomes imperative for Nigeria to stay abreast in the field of power generation.

Nigeria's energy landscape faces a complex challenge of balancing the need for cost-effective electricity generation with the imperative of reducing greenhouse gas emissions to combat climate change. The country's energy sources include gas, hydro, wind and solar each with varying capacities, costs and environmental impacts

The problem at hand is to devise an optimal energy mix that ensures the most efficient allocation of these resources to meet the nation's energy demand while minimizing the economic cost and reducing carbon emissions. This energy mix should align with the available capacity for each source and consider their varying cost-effectiveness.

1. Minimize the total cost of electricity generation by allocating energy sources efficiently.

2. Reduce GHG emissions to meet environmental sustainability targets.

3. Determine the percentage allocation of gas, hydro, wind, and solar to achieve both cost-efficiency and GHG emissions reduction.

The problem encompasses the utilization of the following key variables:

- Energy source percentages (Gas, hydro, wind, and solar).

- Energy capacity constraints.

- Total energy demand.

- Cost of electricity generation from each source.

- GHG emissions per unit of electricity generated.

- Maximum allowable GHG emissions.

This problem statement outlines the critical need for an optimized energy mix in Nigeria, balancing economic and environmental objectives. It forms the basis for developing and implementing a robust solution that can guide energy policy, planning, and decision-making in the country.

1.4 RESEARCH QUESTIONS AND HYPOTHESIS.

This study is concerned with different aspects and aims to answer the following questions:

1. **Optimal Energy Mix Composition:** What is the optimal distribution of percentages among gas, hydro, wind, and solar capacities in the Nigeria Energy Mix to achieve the lowest overall cost of electricity generation? **Hypothesis:** There exists a specific distribution of percentages among gas, hydro, wind, and solar capacities that minimizes the overall cost of electricity generation in the Nigeria Energy Mix.
2. **Economic Viability:** How do different energy mix scenarios impact the overall economic viability of electricity generation, considering costs associated with each energy source? **Hypothesis:** Different energy mix scenarios significantly impact the economic viability of electricity generation, with variations in costs associated with each energy source.
3. **Environmental Impact**: What are the environmental implications of various energy mix configurations, and how do these scenarios contribute to the reduction of greenhouse gas emissions? **Hypothesis:** Various energy mix configurations exhibit distinct environmental implications, and certain scenarios contribute significantly to the reduction of greenhouse gas emissions.
4. **Sensitivity to Capacity Changes:** How sensitive is the optimized energy mix to changes in total energy generation capacity, and what are the implications for both cost and carbon

emissions? **Hypothesis:** The optimized energy mix is sensitive to changes in total energy generation capacity, and alterations in capacity influence both cost and carbon emissions.

5. **Role of Renewable Energy:** What role do renewable energy sources (hydro, wind and solar) play in achieving the optimal energy mix, and how does their inclusion contribute to sustainability goals? **Hypothesis:** Renewable energy sources (hydro, wind and solar) play a crucial role in achieving the optimal energy mix, and their inclusion contributes substantially to sustainability goals.
6. **Cost-Emissions Trade-off:** To what extent can the optimization model strike a balance between minimizing costs and achieving significant reductions in carbon emissions? **Hypothesis:** The optimization model can effectively balance the trade-off between minimizing costs and achieving substantial reductions in carbon emissions within the Nigeria Energy Mix.
7. **Impact of Policy Interventions:** How would different policy interventions, such as incentives for renewable energy or carbon pricing, influence the recommended energy mix and associated outcomes? **Hypothesis:** Different policy interventions, such as incentives for renewable energy or carbon pricing, have a discernible impact on the recommended energy mix and associated economic and environmental outcomes.
8. **Long-term Investment Strategies:** What are the long-term investment strategies that emerge from the optimized energy mix, and how do these align with sustainable and economically sound energy development? **Hypothesis:** The optimized energy mix suggests specific long-term investment strategies aligned with sustainable and economically sound energy development in Nigeria.
9. **Resilience to Fluctuations:** How resilient is the optimized energy mix to fluctuations in fuel prices, technology costs, and other external factors that may impact the economic and environmental performance? **Hypothesis:** The optimized energy mix demonstrates resilience to fluctuations in fuel prices, technology costs, and other external factors, maintaining economic and environmental performance.
10. **Transferability to Different Capacity Scenarios:** To what extent can the findings and optimization model be transferred or adapted to different energy generation capacity scenarios, ensuring broader applicability? **Hypothesis:** The findings and optimization model are transferable and adaptable to different energy generation capacity scenarios, ensuring their broader applicability beyond the specific capacity range considered in this study.

These research questions aim to guide the investigation into the complexities of optimizing the Nigeria Energy Mix, exploring the intricate balance between economic considerations and environmental sustainability. They address key aspects such as composition, viability, sensitivity, and the role of policy in shaping an energy landscape that is both economically prudent and ecologically responsible. In addition, these hypotheses serve as foundational statements to be tested and validated through rigorous research and analysis of the Nigeria Energy Mix Optimization Model (NEMOM). They guide the exploration of relationships between key variables and contribute to a comprehensive understanding of the complex dynamics involved.

1.5 AIM AND OBJECTIVES OF THE STUDY

Achieving the required pace and scale for the energy transition necessitates nearly complete decarbonization of the electricity sector. This entails utilizing renewables, enhancing energy efficiency, and fostering flexibility in power systems.

This project adopts a systematic approach, delving into the supply, distribution, and utilization of energy in diverse forms, coupled with low-carbon sources (specifically renewable technology) for power generation in Nigeria. The focus is on assessing the cost variations associated with each option to determine an optimal combination that not only addresses the energy challenge but also minimizes costs and reduces CO_2 emissions.

In pursuit of these objectives, novel technologies are under development, and the power systems themselves are undergoing transformations. The emphasis is not solely on developing or deploying individual technologies but understanding the operational context and cost implications of these technologies.

The study's objective is to devise a novel method for identifying the optimal energy mix for Nigeria's power sector. To realize this goal, an Excel optimization model encompassing various economic, environmental, and technical aspects will be formulated.

Objectives:

The objectives of this study are as follows:

- To evaluate the energy sources available to us in Nigeria and their accessibility/exploitability
- To design an energy mix that optimizes power generation with a drive towards decarbonizing the electricity sector

- To carry out carbon emission analysis on each energy mix combination in order to determine how much carbon emissions come from each source and in turn decide the best combination option
- Every decision comes with consequences. Hence, economic analysis would be carried out on each combination to evaluate the cost implication of each option.

1.6 SCOPE OF THE STUDY

The solution involves an optimization model based on linear programming, considering the decision variables, constraints, and objectives that align with the aims and objectives of the study. The model aims to find the optimal combination of energy sources that achieves the lowest cost and minimizes GHG emissions.

Solving this problem is of paramount importance for Nigeria's energy sector and its commitment to environmental responsibility. The optimal energy mix will have a direct impact on economic stability, energy security, and environmental sustainability, contributing to a brighter and more sustainable energy future.

The challenges include determining the fixed percentages for hydro and establishing a balanced ratio for the remaining energy sources based on cost differences. Additionally, practical implications, data accuracy, and the validation of model results against real-world scenarios are key challenges to address.

1.7 ORGANIZATION OF THE STUDY

This research is presented in five (5) Chapters. The background and Introduction to the study is presented in Chapter 1. A literature review to improve our understanding of the energy mix optimization and key concepts is presented in Chapter 2. Chapter 3 covers the study methodology while Chapter 4 presents the results obtained from the study, observations, and discussion of results. Chapter 5 covers the conclusions and recommendations proposed for future research to improve the present study.

CHAPTER 2: LITERATURE REVIEW

In this chapter, detailed literature review of major related publications will be presented to create a nexus between this study and those published by many scholars across the globe. It is intended to improve our understanding of the major concepts introduced in this study.

2.0 INTRODUCTION

Optimizing the energy mix entails finding the best combination of energy sources and technologies to meet the energy needs and goals of a country or region in the most efficient, sustainable, reliable and affordable way. When considering the optimal energy mix, there is no one-size-fits-all approach, as the optimal energy mix depends on various factors which may include but are not limited to:

- The demand and consumption patterns of different sectors such as residential, commercial, industrial, transport, etc.
- The availability and potential of different energy sources (oil, coal, gas, wind, hydro, solar, biomass, etc.)
- The cost and benefits of different energy technologies such as generation, transmission, distribution, storage, efficiency, etc.
- The environmental and social impacts of different energy choices such as greenhouse gas emissions, air pollution etc.
- The policy and regulatory framework that support or hinder different energy options such as taxes, subsidies, tariffs, standards, targets, etc.

Therefore, the optimal energy mix may vary from country to country or from region to region depending on their specific circumstances and preferences. However, some general principles that can guide the planning of the optimal mix are as follows:

- Diversifying the energy sources to reduce dependence on imports and enhance energy security and resilience.
- Increasing the share of renewable energy sources to reduce greenhouse gas emissions and environmental impacts

- Improving energy efficiency and conservation to reduce energy demand and save resources.
- Reforming the power sector to increase tariffs, reduce losses, attract investment and enhance reliability.
- Promoting local manufacturing and innovation to create jobs and income opportunities

2.1 GLOBAL AND REGIONAL ENERGY MIX TRENDS

There is a global trend towards increasing the proportion of renewable energy sources, such as solar, wind, hydropower, and bioenergy. Fossil fuels have historically dominated the global energy landscape since the industrial revolution, with oil at 31%, coal at 21%, natural gas at 23%, nuclear at 5%, and renewables at 14% of the total 606EJ energy supply in 2019 (IEA, 2021). ***Figure 2.1*** shows the global annual average change in energy production by fuel between 1971 and 2019.

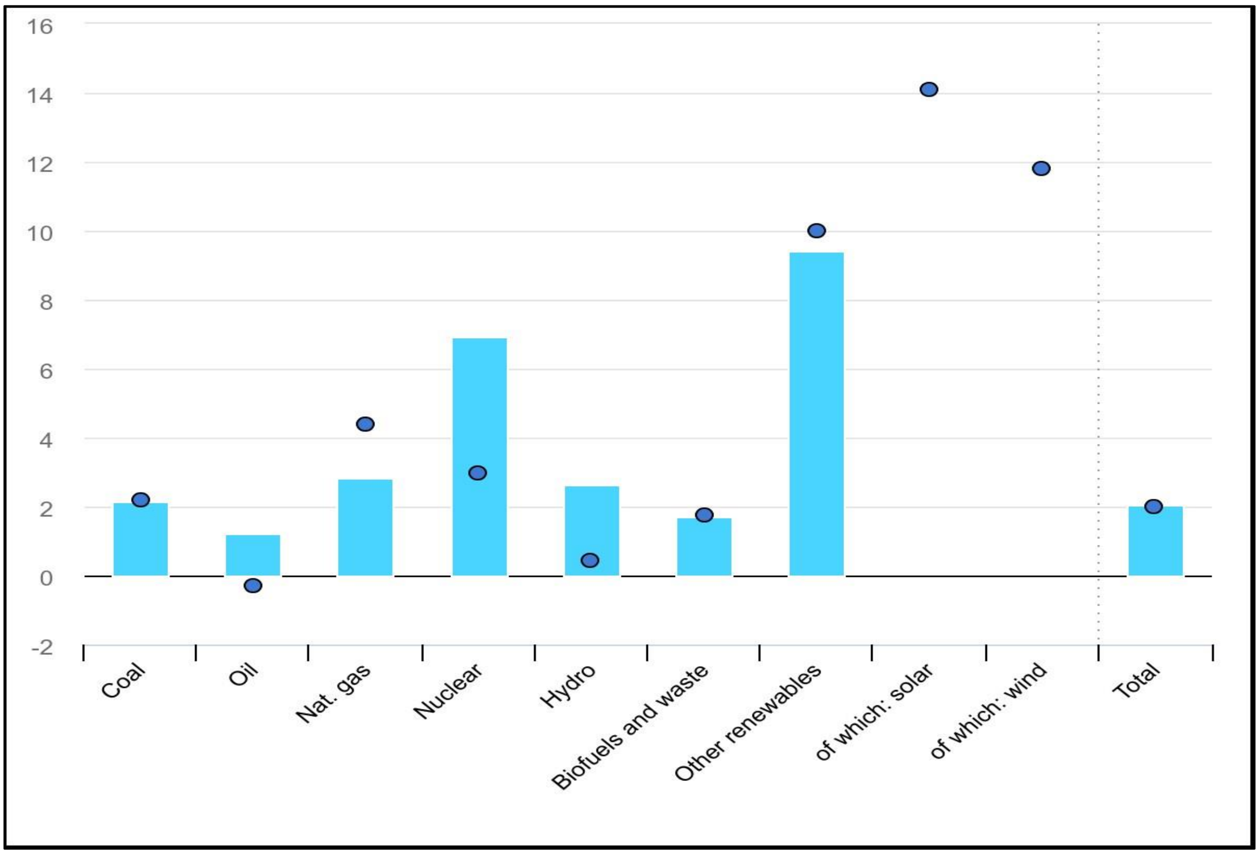

Figure 2.1: Global annual average change in energy production by fuel, 1971-2019 (IEA, 2021)

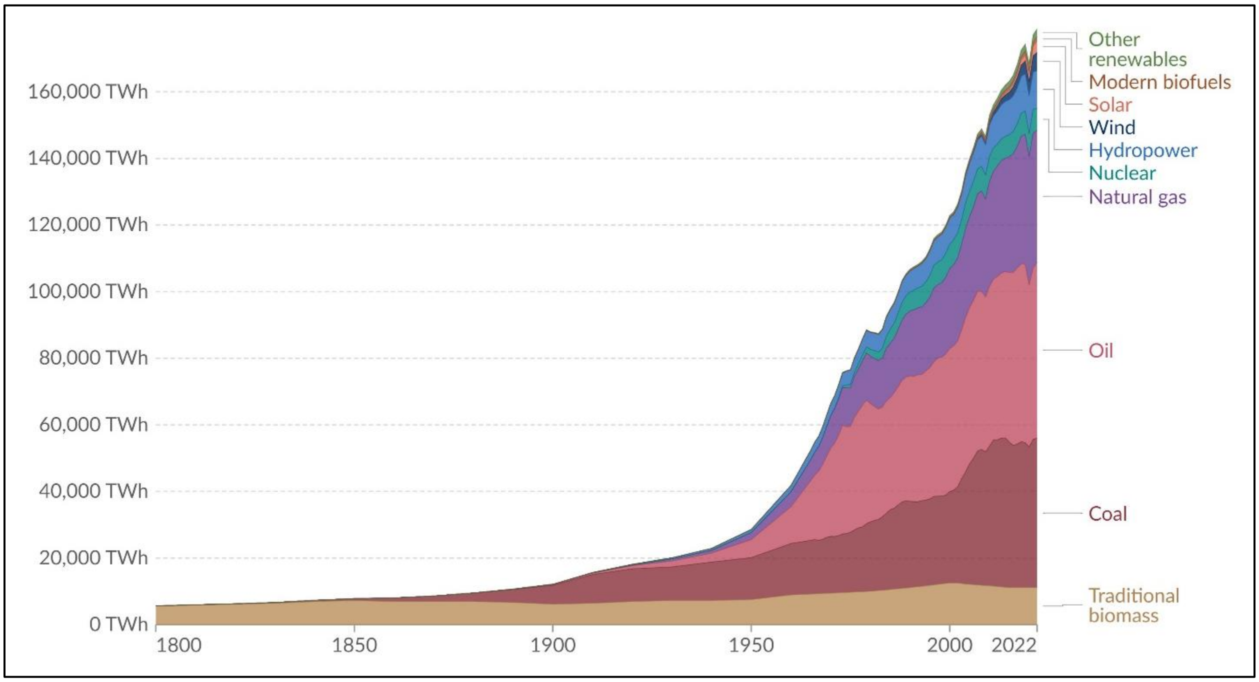

Figure 2.2: Global primary energy consumption by source (Our world in Data, 2020)

Despite coal's abundance, environmental regulations are limiting and gradually phasing out its production technology. Many countries are reducing reliance on coal due to environmental concerns and shifting towards cleaner alternatives. The global energy mix has seen a decrease in coal's share, with increased focus on phasing out or upgrading existing coal-fired power plants. Natural gas is viewed as a transitional fuel, with varying growth degrees influenced by factors like availability, infrastructure, and policy frameworks. Nuclear energy remains a stable component in some regions, facing challenges in new project development due to cost and safety considerations, and public perceptions.

Efforts are globally concentrated on improving energy efficiency, embracing energy-efficient technologies, smart grid systems, and adopting energy conservation practices. Governments and industries are investing in renewable technologies to reduce carbon emissions and enhance sustainability. European countries are leading in renewable energy adoption, committing to ambitious targets and investing heavily in wind, solar, and hydropower. Asia, particularly China and India, is experiencing significant growth in energy demand, investing in both coal and renewables to diversify and reduce emissions. The United States is transitioning away from coal towards natural gas and renewables, influenced significantly by increased shale gas production.

Middle Eastern countries, rich in oil and gas reserves, are exploring renewables to diversify their energy mix and meet domestic demand. Many African nations focus on increasing energy access, incorporating renewables, and emphasizing off-grid and decentralized solutions for rural electrification.

Energy mix trends are subject to change based on policy shifts, technological advancements, and economic and environmental priorities (IRENA, 2023).

While global energy remains heavily dependent on fossil fuels, there is notable stability and growth in renewable energy usage, particularly in solar, hydro, wind, geothermal, and biomass (Weforum, 2023). The transition in the energy sector is characterized by changes in consumption patterns, economic growth, environmental costs, and advancements in technology for efficient renewable energy generation. Despite challenges, including volatility in energy and food prices, the transition towards cleaner and sustainable energy sources is evident. Energy security, defined by factors like availability, affordability, and sufficiency, plays a crucial role in achieving sustainability goals (Fang, D. et al, 2018).

The global push for decarbonization to mitigate climate change effects requires strategic and sustainable energy solutions. Advances in the renewable sector, including solar, wind, biomass, and hydropower, contribute up to 27% of the global electric energy mix. However, fossil energy sources, particularly coal, still dominate the global electricity supply, accounting for 37% of the total worldwide, while natural gas is emerging as a cleaner source, generating up to 23% between 2000 and 2019 (Wadim Strielkowski et al, 2021).

As the world gravitates towards clean energy, the importance of gas in the Nigerian economy cannot be overemphasized as gas is a potent source of electricity that will sustain the much-needed power for national development.

2.2 ENERGY MIX OPTIMIZATION MODELS

Energy mix optimization models are mathematical models that aim to find the best combination of different energy sources to meet the energy demand and supply of a system, while considering various objectives and constraints, such as cost, emissions, security, reliability, and sustainability. Energy mix optimization models can be used to support energy planning and policy making, as well as to evaluate the impact of different scenarios and technologies on the energy system.

To effectively tackle climate change and reduce costs, the energy sector needs to understand how to secure, make affordable, and sustainably achieve future energy provisions.

In this context, numerous factors must be taken into account, including the electrification of energy demand sectors (IPCC, 2022), ensuring a secured supply even during periods with limited renewable power generation (Lund P.D. et all, 2015), and establishing a highly diversified and economically viable array of technologies. Consequently, identifying effective policy measures to encourage the transformation of the energy supply system becomes a complex undertaking. Models are frequently employed to gain insights into potential future scenarios for the energy system, serving as decision support in energy policy and industry (Pfenninger, S. et al, 2014). To examine the adoption of renewable power generation and the deregulation of power markets from a macro perspective, a wide range of energy system models, each with distinct strengths in addressing the aforementioned aspects, has emerged (Ringkjøb HK et al, 2018; Horschig T, Thr¨an D., 2017). A notable category is Energy System Optimization Models (ESOMs) (Hawker GS, Bell KRW, 2020), utilized to observe the potential operation of power plants and technologies for balancing the intermittent power supply of renewable energy sources. These models, characterized by a clearly defined objective function and constraints, offer a user-friendly framework for modeling decision processes and simulating investment decisions when multiple solutions are viable (e.g., employing different technologies for load balancing). Additionally, ESOMs are employed to design future energy systems aligned with relevant political targets, such as greenhouse gas (GHG) mitigation goals (Sasanpour, S. et al, 2021). The purpose of formulating these ideal system designs is to provide templates for navigating the transformation of the system, including setting incentives.

Some examples of energy mix optimization models are:

OPTIMIZATION MODEL OF ENERGY MIX TAKING INTO ACCOUNT THE ENVIRONMENTAL IMPACT: This article (Gruenwald, O., Oprea, D., 2012) proposes a linear optimization model of the energy mix for Indonesia that considers the environmental impact of different energy sources. It uses a multi-objective linear programming approach to minimize the cost and the greenhouse gas emissions of the energy system, and analyzes the optimal scenarios for 2020.

ENERGY MIX OPTIMIZATION FROM ENERGY SECURITY PERSPECTIVE BASED ON STOCHASTIC MODELS: This article (Yaser Kanani Maman, Abbas Maleki, 2022) proposes a framework to incorporate energy security components into the calculation of the optimal energy supply situation. It uses stochastic models to account for the uncertainty and risk of different energy sources and applies the method to the case of Iran.

MILP FORMULATION FOR ENERGY MIX OPTIMIZATION: This article (W. Lyzwa, M. Wierzbowski and B. Olek, 2015) presents a mixed-integer linear programming model for energy mix optimization that considers the rated power of each power generating unit. It uses a genetic algorithm to solve the model and applies it to the case of Poland.

A STUDY OF LONG-TERM ENERGY-MIX OPTIMIZATION MODEL: A CASE STUDY OF JAPAN: This article (Negishi, 2022) presents a long-term energy-mix optimization model that aims to achieve carbon neutrality in the power system. The study models power supply and demand at an hourly granularity and determines the generation capacity that minimizes the long-term energy supply cost. It uses a scenario analysis to evaluate the impact of different policies and technologies on the energy mix and the emissions.

OPTIMIZATION DESIGN OF ENERGY-SAVING MIXED FLOW PUMP BASED ON MIGA-RBF ALGORITHM: This article (Lu, Rong et al, 2021) presents an optimization design of an energy-saving mixed-flow pump based on computational fluid dynamics (CFD) and genetic algorithm. The model uses CFD to simulate the flow field and the performance of the pump, and uses genetic algorithm to optimize the geometric parameters of the impeller and the volute. The model improves the efficiency and the head of the pump.

2.3 NIGERIA'S ENERGY LANDSCAPE

Energy is central for sustainable development, and sustainability can encompass minimum environmental impact, energy security, and affordability to get to the poorest people. This landscape implies the need to analyze the emissions reduction targets considering an environmental perspective along with energy security and affordability for all (F.A. Plazas-Ni˜no et al, 2022).

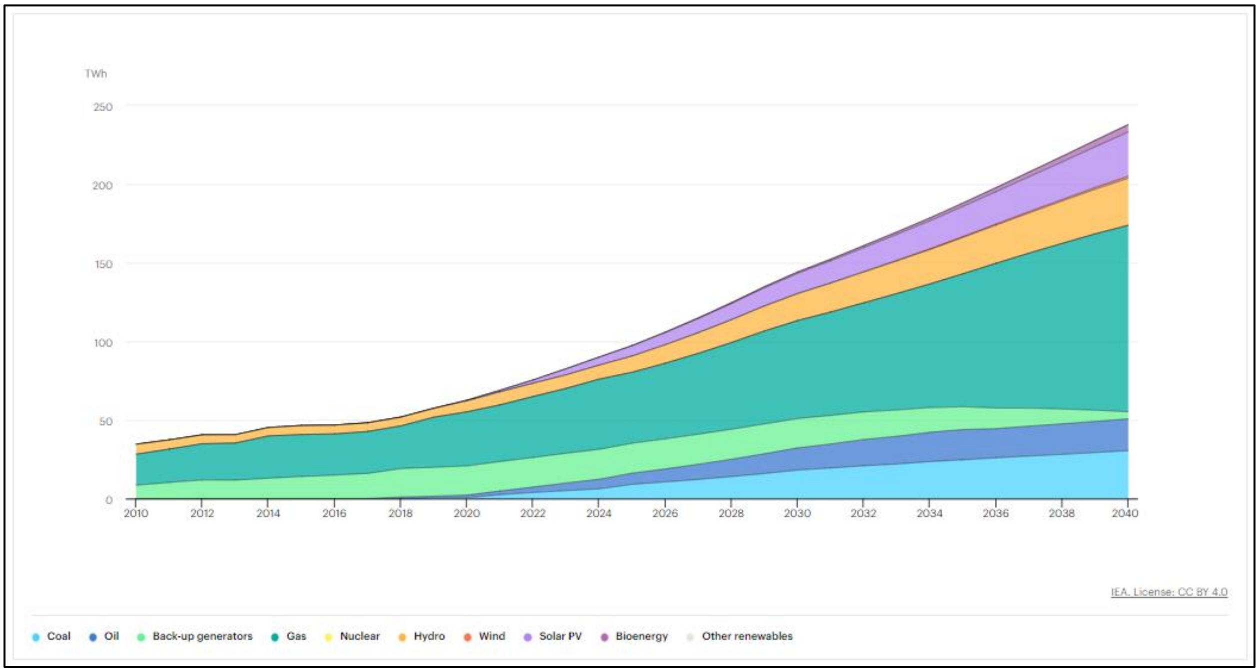

Figure 2.3: Nigeria Electricity distribution by technology in the Africa Case (IEA 2022)

Nigeria's energy landscape is characterized by a mix of traditional, fossil fuel-based, and renewable energy sources. Nigeria's electricity generation relies heavily on fossil fuels, particularly natural gas and oil. The majority of the country's power plants are gas-fired, with some oil-based plants. The capacity for renewable energy, including solar and hydropower, is being expanded. Nigeria has significant potential for renewable energy, especially solar and hydropower. Initiatives are underway to increase the share of renewables in the energy mix, with projects such as the Zungeru Hydropower Plant and various solar power installations. Access to electricity remains a challenge in many parts of Nigeria, particularly in rural areas. Efforts are being made to improve access through grid expansion, off-grid solutions, and decentralized renewable energy projects. Nigeria is known for gas flaring, a byproduct of oil extraction. Efforts to reduce gas flaring and harness associated gas for power generation are ongoing. Policies and regulations aim to encourage investment in gas utilization projects. Nigeria has implemented power sector reforms to address challenges such as inefficiencies, inadequate infrastructure, and low electricity generation. These reforms include privatization initiatives to attract private investment and enhance efficiency. Nigeria is the largest economy in sub-Saharan Africa, but limitations in the power sector constrain growth. The electricity sector in Nigeria generates, transmits and distributes megawatts (MW) of electric power that is significantly less than what is needed to meet basic household and industrial needs. Challenges in Nigeria's energy sector include issues of grid reliability, transmission and distribution losses, financial sustainability of power utilities, the need for increased investment in infrastructure and major power sector planning shortfalls that have kept the sector from reaching commercial viability.

The Nigerian government has articulated policies to promote sustainable energy development, improve efficiency, and diversify the energy mix. These policies include the National Renewable Energy and Energy Efficiency Policy and the Nigerian Power Sector Recovery Program. Off-grid and decentralized energy solutions, such as solar home systems and mini-grids, play a role in improving energy access, especially in areas where extending the main grid is economically challenging. Nigeria collaborates with international organizations, development partners, and investors to support energy projects, enhance technical capacity, and attract financing for sustainable energy initiatives. Innovations in energy storage, smart grid technologies, and digitization are becoming increasingly relevant in modernizing Nigeria's energy infrastructure and improving overall efficiency.

Gas is a major feedstock for electricity generation in Nigeria. About 80% of Nigeria’s grid electricity is generated from gas-fired thermal power plants. Gas is preferred as a source of energy because of its efficiency in energy generation, relatively low per unit cost and low carbon emissions.

2.4 RENEWABLE ENERGY POTENTIAL IN NIGERIA

To mitigate reliance on fossil fuels and mitigate greenhouse gas (GHG) emissions, nations are adopting a suite of policies to stimulate the advancement of renewable energy (RE) (Shiwei YU et al, 2023).

Renewable energy is a clean and sustainable source of energy that can help Nigeria meet its growing energy demand, reduce its dependence on fossil fuels, and achieve its climate and development goals. Renewable energy has considerable potential in Nigeria, especially in solar, wind, hydro, and biomass resources.

According to the Renewable Energy Roadmap for Nigeria (Seán Collins et al, 2023), developed by the International Renewable Energy Agency (IRENA 2023) and the Energy Commission of Nigeria (ECN 2023), Nigeria could increase its renewable energy share from 13% in 2015 to 36% by 2030, and 72% by 2050, with an additional 2030 focus to aid shorter-term policy development. This would require an investment of USD 9.5 billion by 2030 and USD 109.4 billion by 2050, which would generate multiple benefits, such as creating 200,000 jobs, saving 11,000 lives per year from reduced air pollution, and avoiding 208 million tonnes of CO_2 emissions per year by 2050.

Nigeria has substantial renewable energy potential across various sources, contributing to the country's efforts to diversify its energy mix and address energy challenges. Here's an overview of renewable energy potential in Nigeria:

SOLAR ENERGY

Solar energy is the most abundant and widely distributed renewable energy resource in Nigeria, with an average annual solar radiation of about 5.25 kWh/m2/day and a total estimated potential of 427,000 MW (Sadiq A. Goni et al, 2020). The country's geographic location near the equator makes it suitable for solar energy generation. Solar energy can be used for both grid-connected and off-grid applications, such as rural electrification, water pumping, irrigation, and telecommunications. Solar energy can also complement the existing hydro power plants, which are vulnerable to seasonal variations and droughts. According to the IRENA-ECN roadmap, solar energy could account for 30% of the total electricity generation by 2030 and 55% by 2050.

HYDROPOWER

Nigeria has significant hydropower potential, with various rivers and water bodies suitable for hydropower projects. Hydro energy is the most exploited renewable energy resource in Nigeria, accounting for about 17% of the total electricity generation in 2015. Nigeria has a total estimated hydro power potential of 14,750 MW, of which only 1,930 MW has been developed. Hydro energy can be used for both large-scale and small-scale applications, such as grid integration, rural electrification, irrigation, and flood control. Hydro energy can also provide a flexible and dispatchable source of power, which can balance the intermittent nature of solar and wind energy. According to the IRENA-ECN roadmap, hydro energy could account for 4% of the total electricity generation by 2030 and 10% by 2050.

Dams and hydropower plants such as the Kainji, Jebba, and Shiroro contribute to the electricity generation capacity

WIND POWER

Wind energy is another promising renewable energy resource in Nigeria, especially in the northern and coastal regions, where the wind speed ranges from 2 to 10 m/s. Wind energy can be used for both large-scale and small-scale applications, such as grid integration, rural electrification, water pumping, and refrigeration. Wind energy can also provide a reliable and cost-effective alternative to diesel generators, which are widely used in Nigeria. According to the IRENA-ECN roadmap, wind energy could account for 2% of the total electricity generation by 2030 and 7% by 2050. Wind farm initiatives have been explored, with some projects in the planning stages to harness wind energy for power generation.

BIOMASS AND BIOENERGY

Biomass energy is the most widely used renewable energy resource in Nigeria, accounting for about 83% of the total primary energy supply in 2015. Nigeria has a rich biomass resource base, including wood, crop residues, animal wastes, municipal solid wastes, and biogas. Biomass energy can be used for various applications, such as cooking, heating, lighting, power generation, and biofuels production. Biomass energy can also provide a source of income and employment for rural communities, as well as reduce greenhouse gas emissions and deforestation. Biomass reduces carbon emissions by utilizing organic matter, which absorbs carbon dioxide during growth and releases it when burned, making it carbon-neutral compared to fossil fuels (Monthly Energy Review - Biomass Explained, 2023). Additionally, biomass helps mitigate deforestation by incentivizing sustainable forestry practices and utilizing waste materials, thereby reducing the pressure on natural forests and promoting their conservation while also providing economic benefits to rural communities. According to the IRENA-ECN roadmap, biomass energy could account for 0.3% of the total electricity generation by 2030 and 0.4% by 2050.

Initiatives for waste-to-energy projects using organic waste materials are being considered to address waste management challenges. For the scope of this project, we would not be considering biomass and bioenergy.

GEOTHERMAL ENERGY

While geothermal resources are not as extensively explored, there is potential for geothermal energy development, particularly in the central and northern regions of Nigeria.

In general, Renewable energy has a huge potential in Nigeria, but it also faces many challenges and barriers, such as lack of adequate policies, regulations, and incentives, high upfront costs and risks, low public awareness and acceptance, limited technical and institutional capacities, and weak grid infrastructure and management. To overcome these challenges and unlock the full potential of renewable energy, Nigeria needs to adopt a comprehensive and integrated approach, involving all stakeholders and sectors, and addressing the technical, economic, social, and environmental aspects of the energy transition. Some of the key actions and recommendations include:

- Developing and implementing a clear and consistent policy and regulatory framework that supports the development and deployment of renewable energy, such as feed-in tariffs, net metering, tax incentives, and renewable energy targets (Nnaemeka Vincent Emodi, Nebedum Ekene Ebele, 2016).
- Mobilizing and diversifying the sources and mechanisms of financing for renewable energy projects, such as grants, loans, guarantees, equity, bonds, and green funds (Mr. Ananthakrishnan Prasad et al, 2022).
- Enhancing the public awareness and acceptance of renewable energy, through education, information, communication, and demonstration programs (Nor Aisyah Che Derasid et al, 2021).
- Building and strengthening the technical and institutional capacities of the relevant actors and institutions, such as ministries, agencies, utilities, regulators, developers, investors, and consumers (Bank Group Capacity Development Strategy, AFDB, 2010).
- Improving and expanding the grid infrastructure and management, to ensure the reliability, stability, and security of the power system, and to facilitate the integration of variable renewable energy sources, such as solar and wind (Khalid A. Khan et al, 2023).
- Promoting and supporting the development and deployment of off-grid and mini-grid renewable energy solutions, especially for rural and remote areas, where grid extension is not feasible or cost-effective (Emília Inês Come Zebra et al, 2021).
- Fostering the regional and international cooperation and collaboration on renewable energy, through sharing of best practices, experiences, technologies, and resources.

While Nigeria has made progress in tapping its renewable energy potential, there are ongoing efforts to scale up these initiatives, enhance grid integration, and overcome challenges related to financing, regulatory frameworks, and infrastructure development. The country’s renewable energy sector is expected to play a significant role in meeting growing energy demand and addressing sustainability goals.

Renewable energy can help Nigeria not only meet its energy needs, but also power sustainable economic growth and create jobs while achieving global climate and sustainable development objectives. Renewable energy is the future of Nigeria, and the time to act is now.

2.5 ENERGY POLICY AND REGULATORY FRAMEWORK

Nigeria has developed a comprehensive energy policy and regulatory framework to guide the development, management, and sustainability of the country's energy sector. Here are the key components of the energy policy and regulation framework in Nigeria:

National Energy Policy: The National Energy Policy of Nigeria provides a broad and strategic vision for the country's energy sector. It outlines objectives, targets, and strategies for achieving a balanced energy mix, improving energy access, and ensuring sustainability.

National Renewable Energy and Energy Efficiency Policy (NREEEP): The NREEEP focuses specifically on promoting renewable energy and energy efficiency in Nigeria. It aims to increase the share of renewable energy in the national energy mix and improve energy efficiency across the sectors.

Power Sector Reform Act (PSRA): The Power Sector Reform Act of 2005 is a fundamental piece of legislation that laid the groundwork for the privatization and liberalization of Nigeria's power sector. It created regulatory bodies and established the framework for private sector participation.

Regulatory Agencies: NERC (Nigerian Electricity Regulatory Commission): NERC is the regulatory body responsible for regulating the electricity industry, ensuring fair competition, and protecting the interests of consumers.

NERC Act 2005: The NERC Act empowers NERC to issue licenses, set tariffs, and establish standards for the electricity industry.

Rural Electrification Strategy and Implementation Plan (RESIP): The RESIP outlines strategies to improve energy access in rural and underserved areas. It includes provisions for off-grid and decentralized energy solutions, promoting renewable energy in rural electrification projects.

Gas Master Plan: The Gas Master Plan focuses on harnessing Nigeria's abundant natural gas resources for domestic use and export. It outlines policies and strategies for gas development, infrastructure, and utilization.

National Renewable Energy Action Plan (NREAP): The NREAP provides a roadmap for the integration of renewable energy sources into Nigeria's energy mix. It includes targets, incentives, and policy measures to promote the deployment of renewable energy technologies.

Electricity Power Sector Reform (EPSR) Roadmap: The EPSR Roadmap outlines the government's plans for achieving a sustainable and efficient electricity sector. It addresses issues such as privatization, market reforms, and capacity expansion.

Feed-in Tariff (FiT) System: Nigeria has introduced a Feed-in Tariff system to encourage investment in renewable energy projects. The FiT provides fixed payments to renewable energy producers, offering financial incentives for clean energy development.

Energy Efficiency Standards and Labeling Program: Nigeria has established energy efficiency standards and labeling programs for appliances and equipment to promote energy conservation and reduce energy consumption.

2.6 CASE STUDIES AND RESEARCH IN NIGERIA

To optimize the Nigeria energy mix would require the understanding of previous works specifically tailored to the energy mix.

This section analyzes a couple of studies that have been done in the past for a better understanding of the Nigeria energy mix.

Some case studies relating to the energy mix optimization for Nigeria are:

- **Optimizing the performance of hybrid renewable energy systems to accelerate a sustainable energy transition in Nigeria: A case study of a rural healthcare center in Kano** (Abdulfatai Olatunji Yakub et al, 2022): This initiative conducted a thorough examination to model, simulate, and evaluate various configurations of a hybrid energy system (HES) designed for a rural healthcare facility in northern Nigeria.
- **Optimum predictive modelling for a sustainable power supply mix: A case of the Nigerian power system** (Hanif Auwal Ibrahim, Michael Kweneojo Ayomoh, 2022): This investigation aimed to determine the most effective power supply mix using the GAMS model. The primary objectives were to reduce costs, minimize emissions, and foster job creation.
- **Optimal energy mix for electricity generation in Nigeria** (Okeke, 2022): This research provides several recommendations for refining Nigeria's energy mix, including avoiding the installation of new gas plants, maximizing the potential of hydro resources, and increasing investments in solar energy, among other strategies.

- **A Novel Framework for Cost Optimization of Renewable Energy Installations: A Case Study of Nigeria** (Aliyu Aliyu and Neyre Tekbiyik-Ersoy, 2019): The framework and models outlined in this paper were intentionally crafted to offer flexibility, making them adaptable for application in diverse countries or regions. This adaptability facilitates the integration of current generation capacities with a heightened utilization of Renewable Energy Sources (RES), including wind and solar, as exemplified in the case study.
- **Optimal-Mix-Model Structure as an Alternative Methodological Structure for the Nigerian Energy Calculator 2050** (Khaleel, Ahmad Garbaa and Chakrabarti, Milindo, 2019): This paper examines the modeling framework of NECAL2050 and highlights certain crucial local factors in Nigeria, such as the energy demands of agriculture and the significance of renewables, which are not accounted for in the model. In response to these omissions, an alternative modeling structure, the Optimal-Mix-Model, is suggested. This proposed model incorporates the previously missing elements and aligns with the specific conditions present in Nigeria.

2.7 COST EFFECTIVENESS ANALYSIS

Energy is central for sustainable development, and sustainability can encompass minimum environmental impact, energy security, and affordability to get to the poorest people. This landscape implies the need to analyze the emissions reduction targets considering an environmental perspective along with energy security and affordability for all (F.A. Plazas-Ni˜no et al, 2022).

The optimization paradigm is instrumental by considering demand, cost, and environmental restrictions to find the optimum energy mix (Weber J et al, 2019), recognizing ESOMs as tools to support decision processes for decarbonization and energy policy in the evaluation of long-term strategies for countries (Kueppers M et al, 2021).

2.8 CARBON EMISSION REDUCTION EFFORTS

There is a strong need to reduce greenhouse gas emissions in order to deal with climate change. In the power sector, changing the power generation method in the medium and long term is needed to reduce greenhouse gas emissions (Negishi, 2022).

In the first two decades of the 21st century, the purpose of energy models was predominantly in favor of assessing the deployment of renewable energies, and GHG emissions reduction became a fundamental objective of energy system modelling (Lopion P et al, 2018).

2.9 CHALLENGES AND CONSTRAINTS

Access to clean modern energy services is an enormous challenge facing the African continent (Nigeria being at the forefront) because energy is fundamental for socioeconomic development and poverty eradication (Nnaemeka Vincent Emodi, Nebedum Ekene Ebele, 2016)

Clean energy underpins the global effort to shift towards a sustainable future. While scaling up renewables in the energy mix can sharply reduce one major source of CO_2 emission, integration of a large share of renewable energy poses an increasing challenge to power system stability.

Renewable energy sources (RES) are expected to account for more than half of 21st century new energy generation. With RES penetration on an upward trajectory, managing grid stability becomes a top priority with three significant challenges:

- Ensuring sufficient flexibility for power system operations and supply
- Tackling increased operational complexity of the power system
- Integrating inverter-connected device

The integration of a large share of RES in the energy mix means potentially significant power injection during peak load hours, which requires more system flexibility to balance energy supply and demand. The swift change in energy supply will also compound operational complexity by demanding rapid and significant adjustments of conventional energy providers.

The challenge to maintain grid stability differs significantly by country and region. Hence, having flexible and dispatchable energy sources – such as hydropower and gas-fired generation plants, can offset the variability introduced by RES.

CHAPTER 3: METHODOLOGY

3.0 INTRODUCTION

The research methodology employs a quantitative approach, utilizing mathematical optimization techniques and scenario-based analysis. Decision variables are defined to represent the percentage allocation of gas, hydro, wind, and solar energy sources. The model integrates data on capacity, energy demand, cost per megawatt and CO_2 emissions to assess different energy mix scenarios. Scenario results are visualized using graphs and chats that enable policy makers and stakeholders to make informed decisions.

Major steps in the methodology include model formulation and evaluation to determine the applicability of different energy options for the Nigeria energy mix.

3.1 OPTIMIZATION MODEL DEVELOPMENT

Figure 3.1 shows the workflow used for the development of the optimization model adopted for this research.

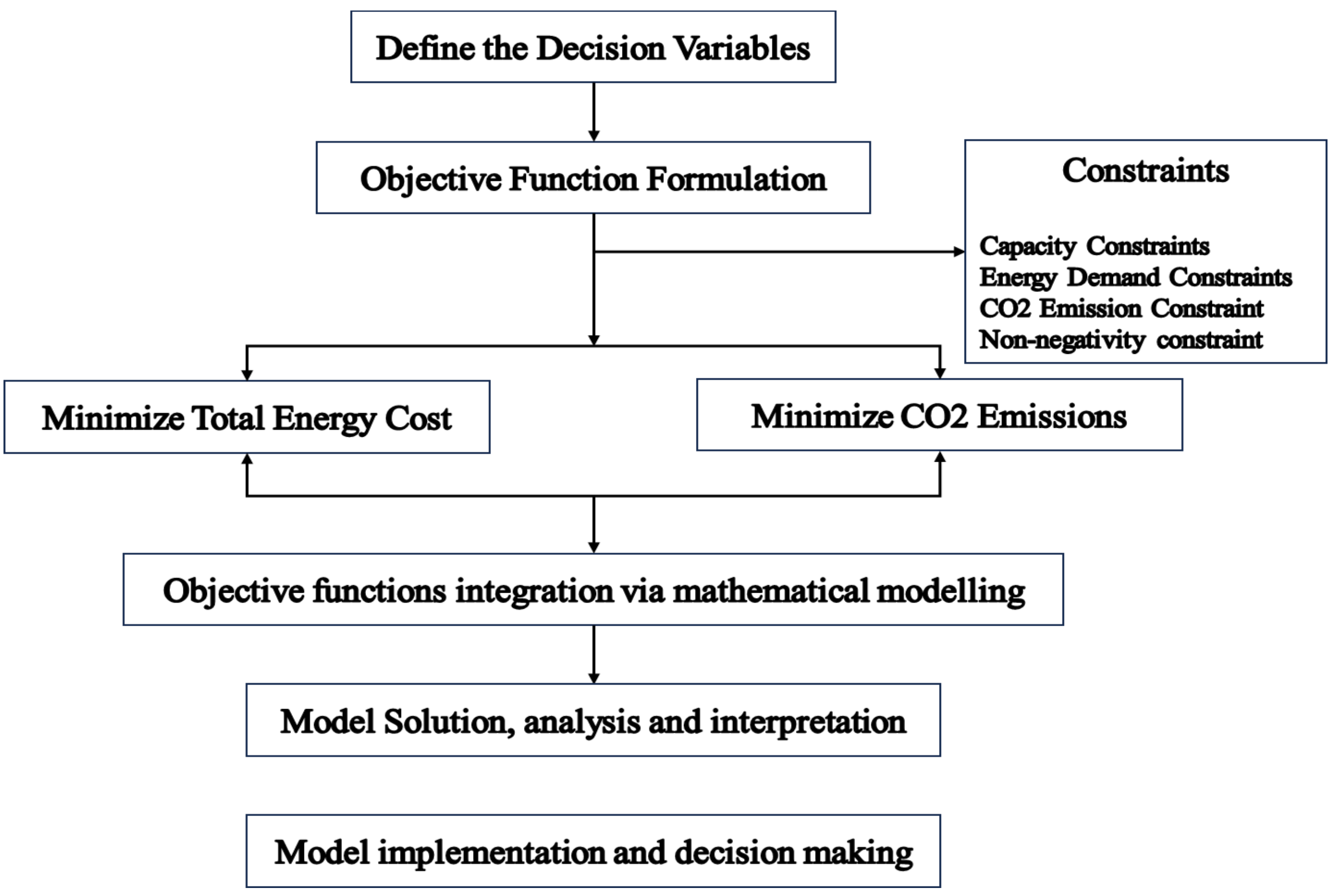

Figure 3.1: Optimization Model Development Workflow

The model development process systematically defines the problem, translates it into mathematical equations and allows for the optimization of the energy mix based on specific goals (i.e., the objective functions), constraints and available data. It provides a structured framework for making informed decisions about the energy mix in Nigeria.

3.2 OPTIMIZATION PARAMETERS AND CONSTRAINTS

The goal of optimization is to find the value of the decision variables that optimizes the objective function while satisfying the constraints.

Here we define the objective functions, decision variables and constraints employed for this study and the steps taken to arrive at reasonable values for each.

The selection of appropriate parameters for the optimization model was accomplished by the careful and detailed scrutiny of the percentages for each mix alongside the use of the Levelized Cost of Energy (LCOE) to determine cost. Basic assumptions for this model would be discussed in detail.

3.2.1 OBJECTIVE FUNCTIONS

The objective functions in the proposed energy mix optimization model serve as the core criteria that the model seeks to optimize. In this case, the model has the following primary objectives:

3.2.1.1 Minimize the total cost of electricity generation while meeting energy demand

This objective function is designed to minimize the total cost of electricity generation in the energy mix. It considers the cost associated with each energy source (Gas, hydro, wind and solar) and the decision variables and determines the proportion of electricity generated from each source. The goal is to find the combination of energy sources that provides the required electricity at the lowest overall cost

$$Total\ Cost\ (C_t) = C_g \times X_g + C_h \times X_h + C_w \times X_w + C_s \times X_s \ldots\ldots\ldots\ldots\ldots\ldots (3.1)$$

$$Where\ C_g = Cost\ of\ electricity\ generation\ from\ gas$$

$$C_h = Cost\ of\ electricity\ generation\ from\ hydro$$

$$C_w = Cost\ of\ electricty\ generation\ from\ wind$$

$$C_s = Cost\ of\ electricity\ generation\ from\ solar$$

$$X_g = Percentage\ of\ electricity\ generated\ from\ gas$$

$$X_h = \text{Percentage of electricity generated from hydro}$$

$$X_w = \text{Percentage of electricity generated from wind}$$

$$X_s = \text{Percentage of electricity generated from solar}$$

NOTE: All costs are based on the Levelized Cost of Energy (LCOE)

The total cost of generation is the sum of the generation cost for each energy source based on the percentage allocation for each energy mix. Data used for this analysis were adapted from the Levelized Cost of Energy (Lazard, 2023) which is the principal tool for comparing the plant-level unit costs of different baseload technologies over their operating lifetimes. The LCOE is a measure of the average net present cost of electricity generation for a generator/energy source over its lifetime. It is used for investment planning and to compare different methods of electricity generation on a consistent basis. The LCOE constitutes an important reference for policy making and modelling. Historically, the LCOE concept was developed in order to help choose between different dispatchable baseload technologies in regulated systems. Low, high and average indicate the cost range.

For each energy source, there is usually an upper threshold (maximum) and a lower threshold (minimum) value determined by the LCOE. However, we used the average (i.e. maximum – minimum/2) cost in this study.

LCOE is given by the formula below:

$$LCOE = P_{MWh} = \frac{\sum(Capital_t + O\&M_t + Fuel_t + Carbon_t + D_t) * (1+r)^{-t}}{\sum MWh(1+r)^{-t}} \ldots\ldots\ldots\ldots (3.2)$$

$Where$:

$P_{MWh} = Levelized\ cost\ of\ electricity$;

$MWh = The\ amount\ of\ electricity\ produced\ annually\ in\ MWh$;

$(1+r)^{-t} = The\ real\ discount\ rate\ corresponding\ to\ the\ cost\ of\ capital$;

$Capital_t = Total\ capital\ construction\ costs\ in\ year\ t$;

$O\&M_t = Operation\ and\ maintenance\ costs\ in\ year\ t$;

$Fuel_t = Fuel\ costs\ in\ year\ t$;

$Carbon_t = Carbon\ costs\ in\ year\ t$;

$D_t = Decommissioning\ and\ waste\ management\ costs\ in\ year\ t$.

3.2.1.2 Reducing the CO_2 emission from each mix

This objective function addresses the reduction of CO_2 emissions. It calculates the total CO_2 emissions associated with the electricity generation by each source. E_g, E_h, E_w and E_s represent the CO_2 emissions per unit of electricity generated from gas, hydro, wind and solar respectively. By minimizing this expression, the model aims to decrease CO_2 emissions, contributing to environmental sustainability.

$$Total\ CO_2\ emissions\ (E_t) = E_g \times X_g + E_h \times X_h + E_w \times X_w + E_s \times X_s \dots\dots\dots\dots\dots (3.3)$$

The energy mix optimization model seeks to find a balance between these two objectives. It aims to minimize the total cost of electricity generation while simultaneously reducing CO_2 emissions. The model will identify the decision variables that achieve the trade-off, ensuring cost effectiveness and environmental responsibility in the energy mix. The specific balance between cost and emission reduction can be adjusted by modifying the constraints in the objective functions to align with the desired policy goals.

3.2.2 DECISION VARIABLES

The decision variables for optimizing the Nigeria energy mix are the variables that affect the choice of the best combination of energy sources to meet the electricity demand, reduce the cost and achieve the environmental and social goals of Nigeria. These decision variables are essential because they allow the optimization model to find the optimal mix of energy sources by specifying how much of the energy supply should come from each source. The model's objective is to minimize cost and reduce CO_2 emissions while adhering to constraints related to capacity, demand and emissions. By adjusting these variables, you can find the most cost-effective and environmentally friendly energy mix for a given set of constraints and objectives.

The decision variable in this case are the percentages of electricity generated from each source and are explained as follows:

1. **The percentage of electricity generated from gas (X_g)**: This is the decision variable that determines the proportion of the total electricity generation (G_t) that comes from

gas. Natural gas is by far the most common source for electricity production in Nigeria. Today, 80% of power generation comes from gas. As such the gas percentage was modeled based on this information. In this case, we considered two different generation scenarios for gas; Net gas (X_{ng}) and gross gas (X_{gg}). We chose a range of net gas percentages from 0 to 80% for each total energy generation. This was then multiplied by the net energy generation which was calculated by subtracting the electricity generated by hydro (G_h) from the total electricity generated (G_t) and then used to determine the gross percentage of gas in the mix. This adjustment was necessary in order to ensure that the energy mix adds up to 100%. This illustrates a rule-based approach to allocating energy sources based on the available capacity in Nigeria.

$$Gross\ gas, X_{gg} = \frac{X_{ng} \times (G_t - G_h)}{G_t} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.4)$$

2. **The percentage of electricity generated from hydro (X_h)**: This decision variable determines the proportion of electricity generation from hydroelectric power (G_h). We fixed the percentage for hydro in this model on the basis of the available hydro capacity in Nigeria which is approximately 10GW. Therefore, for every total energy (G_t) generated in the model, the hydro percentage was determined by taking the 10GW hydro potential and dividing it by the total energy. For example, for a total energy generation of 25GW, the percentage electricity generated from hydro would be (10/25) which amounts to 40%. This is a practical constraint as hydro capacity is generally limited by geographical factors, seasonality and rivers that can be dammed. The general formula for X_h is given by:

$$X_h = \frac{G_w}{G_t} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.5)$$

3. **The percentage of electricity generated from wind (X_w)**: This decision variable indicates the proportion of electricity generation from wind power. After allocating the percentages for gas and hydro, the remaining energy was allocated between wind and solar in the ratio of 1:3. This ratio is based on cost considerations because following the LCOE standards, the cost of wind is approximately three times that of solar. This is a practical approach to distribute the remaining energy as it ensures a balance in the energy mix. Hence the formula for calculating X_w is given by:

$$X_w = \frac{G_t - G_g - G_h}{G_t \times 4} \dots\dots\dots\dots\dots\dots\dots\dots\dots (3.6)$$

4. **The percentage of electricity generated from solar (X_s)**: This decision variable determines the proportion of electricity generated from solar power. This percentage was determined by multiplying the percentage of electricity generation from wind by 3 and is given by:

$$X_s = X_w \times 3 \dots\dots\dots\dots\dots\dots\dots\dots\dots (3.7)$$

3.2.3 CONSTRAINTS

The constraints in the energy mix optimization model are essential conditions that must be satisfied to ensure that the model's results are practical and aligned with specific goals. In the proposed model, the following constraints are applied:

1. **Energy Capacity Constraints**: These constraints restrict the decision variables to be within the available capacity of each energy source. They ensure that the energy mix does not exceed the physical limits of the existing infrastructure for each energy source. For example, the hydro constraint ensures that for each mix, the hydro capacity does not exceed 10GW.

$$X_g \leq gas\ capacity$$

$$X_h \leq hydro\ capacity$$

$$X_w \leq wind\ capacity$$

$$X_s \leq solar\ capacity$$

2. **Energy Demand Constraint**: The energy demand constraint ensures that the sum of the electricity generated from each energy source equals the total energy demand. It guarantees that the energy mix satisfies the energy needs of the system and avoids over-generation and under-generation.

$$X_g + X_h + X_w + X_s = Total\ energy\ demand$$

3. **CO_2 Emission Constraint:** This constraint limits the total CO_2 emissions resulting from electricity generation. It is based on the CO_2 emissions per unit of electricity generated by

each source. The sum of CO_2 emissions must not exceed the specified maximum threshold, contributing to the reduction of environmental impacts.

$$E_g \times X_g + E_h \times X_h + E_w \times X_w + E_s \times X_s \leq Max\ CO_2\ emissions$$

4. **Non-negativity Constraints**: These constraints ensure that the percentages of the energy generated from each energy source are non-negative, reflecting that the proportion of energy from each source cannot be negative.

$$X_g \geq 0$$

$$X_h \geq 0$$

$$X_w \geq 0$$

$$X_s \geq 0$$

By imposing these constraints, the model ensures that the resulting energy mix is feasible, meets energy demands, respects capacity limits and complies with CO_2 emissions restrictions. The optimization process aims to find the best combination of energy sources that balances cost-effectiveness and CO_2 emissions restrictions while adhering to these constraints

3.2.4 ASSUMPTIONS

Simplifying assumptions have to be made when performing the cost analysis of generation units to enable comparability of results. The following assumptions were used to model the energy mix for optimization:

1. **Steady state conditions**. The analysis assumes steady state conditions, which might not fully capture the dynamic nature of energy systems affected by variables like demand fluctuations or technological advancements. Examples of these steady state conditions for this model include: fixed energy source percentages
2. **Linear cost modeling**: The cost model assumes consistent cost relationships across the different scenarios. In reality, non-linearities may exist due to factors like economies of scale or technological breakthroughs.

3.3 MODEL FORMULATION

This part of the work was concerned with developing the optimization model to suit different scenarios of energy mix combinations for the Nigerian Power sector. The impact of each energy mix scenario on the environment was then evaluated by calculating the CO_2 emissions.

For the power calculation, we chose a representative mix of energy sources with typical characteristics that are commonly found in Nigeria. As illustrated in this study, the energy sources under consideration for this study are: Gas, hydro, wind and solar. Limiting conditions for each source are based on the natural and technological limits in Nigeria. Nigeria's electricity supply industry is dominated by natural gas, which accounts for about 80% of power generation. The rest comes from oil, mostly from backup generators that are widely used due to frequent power outages. The country also has abundant renewable energy resources such as hydro, solar, wind and biomass but they are largely underutilized. The model was therefore established by a systematic combination of percentages for the energy mix consisting of gas, hydro, wind and solar while considering the constraints and decision variables to satisfy the objective functions. The model explored a ranged of total energy generation scenarios and their impact on the energy mix. This setup allows for a comprehensive analysis of the various energy mix possibilities based on different constraints and percentages.

The key elements of the model are summarized as follows:

- **Total energy generation scenarios:** The model encompasses a wide range of total energy generation scenarios, from 25GW to 200GW. This wide scope allows for the examination of the energy mix under different levels of energy demand. Expanding the analysis to cover total electricity generation ranging from 25GW to 200GW also provides a dynamic perspective on how the energy mix evolves with different levels of overall electricity demand. As the total electricity generation increases, the absolute contributions from each energy source also increase. This causes changes in the percentage distribution and absolute values which impact the energy mix
- **Energy sources:** The model considers four primary energy sources: Gas, hydro, wind and solar.
- **Percentage allocation:** The model uses an approach that provides a simple but systematic way to allocate energy based on available capacity and cost effectiveness. Therefore, the percentage allocation for each energy source was based on the fixed hydro percentage, the net gas percentage and a 1:3 ratio for wind and solar
- **Generated variables:** Several import variables for each scenario were calculated as shown in ***Table 3.1***. These variables included: The gross power distribution, electricity generated by source, generation cost and carbon emissions by source. These variables are useful for

assessing the cost effectiveness and environmental impact of the different energy mix scenarios.

- **Considerations for the energy mix:** The model covers various scenarios for the energy mix in the following ranges: 0% renewables, 0% gas, 10% - 80% net gas, 50% overall gas and net carbon zero. This is to allow for a thorough exploration of the trade-offs between cost, renewable energy integration and carbon emission reduction.

Overall, the excel optimization model is a powerful tool for conducting scenario-based analysis of the energy mix in Nigeria, taking into account multiple variables, cost factors and environmental considerations. It provides a structured way to assess different energy mix options, which can be a valuable tool for decision makers and policymakers in the power sector.

Table 3.1: Typical Analysis for 25GW Power Generation At 10% Net Gas

				Total Energy	25 GW					
Primary Energy	Gross Power Distribution(%)	Net Power Distribution(%)	Cost per MW($ 000,000)			Electricity Generated by Source(GW)	Generation Cost($ 000,000)			Carbon Emission by Source(KT)
			Low	Average	High		Low	Average	High	
Gas	0.06	0.10	0.33	0.63	1.14	1.50	0.49	0.95	1.71	0.61
Hydro	0.40	0.40	1.00	3.51	7.48	10.00	9.96	35.07	74.84	4.07
Wind	0.14	0.14	1.72	2.88	4.04	3.38	5.81	9.71	13.63	1.37
Solar	0.41	0.41	0.53	1.00	2.01	10.13	5.41	10.07	20.31	4.12
Total	1.00	1.04				25.00	21.66	55.80	110.49	-8.95

CHAPTER 4: RESULTS AND DISCUSSION

4.0 INTRODUCTION

This chapter presents the results obtained from this study. The results are discussed to improve our understanding of the technical and economic feasibility of applying different proportions of the energy mix for optimum efficiency and minimal cost alongside environmental sustainability goals.

An optimized energy mix for Nigeria is technically and economically beneficial but would generally require investment in low-carbon technologies compared to current and planned policies.

4.1 RESULTS OF ABSOLUTE GAS CO_2

The analysis presented here describes the behavior of the graph when considering the absolute gas percentage (Only looks at the CO2 emissions from gas, without considering any reductions or offsets from other sources). Based on earlier assumptions, it is only the gas plant that is emitting CO_2 in this model. It is obvious to see that as the share of gas in the generation mix increases, the CO_2 emission increases and vice versa. The results shown in ***Table 4.1*** are used as input parameters to plot the graph in ***Figure 4.1.***

Table 4.1: 125GW Absolute Gas CO_2 Analysis

Net Gas (%)	Overall Gas (%)	Hydro (%)	Wind (%)	Solar (%)	Absolute Gas C02 (KT/MWhr)	Net C02 (KT/MWhr)
10.00	9.20	8.00	20.70	62.10	4.68	-41.51
20.00	18.40	8.00	18.40	55.20	9.36	-32.15
30.00	27.60	8.00	16.10	48.30	14.04	-22.79
40.00	36.80	8.00	13.80	41.40	18.72	-13.43
50.00	46.00	8.00	11.50	34.50	23.40	-4.07
60.00	55.20	8.00	9.20	27.60	28.08	5.29
70.00	64.40	8.00	6.90	20.70	32.76	14.65
80.00	72.00	8.00	4.50	13.50	37.44	24.01

Table 4.1 provides a comprehensive breakdown of the energy mix for a 125GW (Reference Case) total electricity generation scenario with varying net gas percentages.

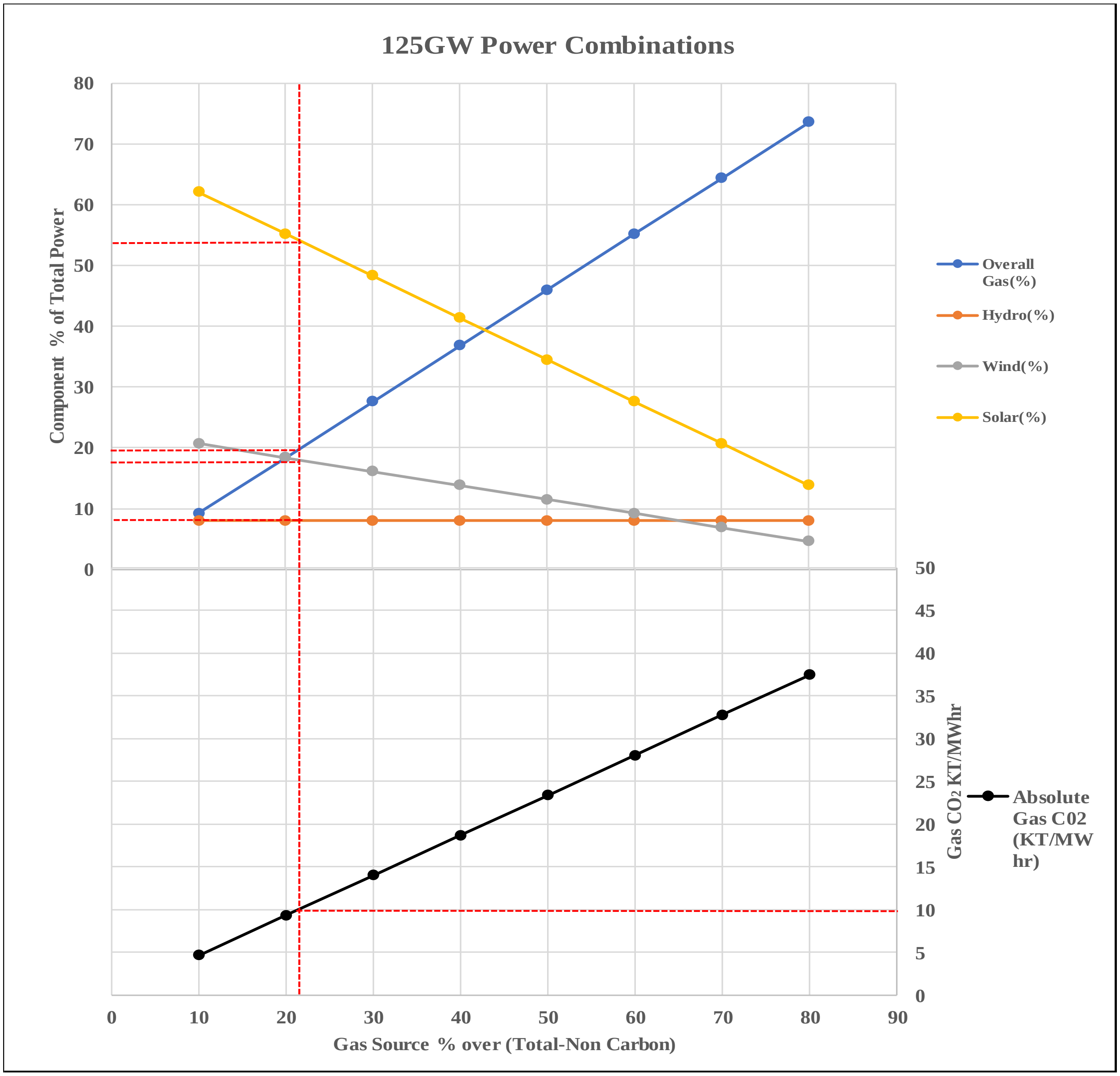

Figure 4.1: Absolute Gas CO_2 analysis for 125GW of Power Generation

As the net gas percentage increases, the overall gas percentage in the energy mix also increases. This leads to a decrease in the percentages of hydro, wind and solar. Absolute gas CO_2 emissions increase with higher net gas percentages. This is an expected trend, as increased reliance on gas, a fossil fuel, generally results in higher carbon emissions. ***Figure 4.1*** is a useful visualization for determining various parameters related to the energy mix. For example, by tracing a line from the secondary axis (Gas CO_2 KT/MWhr) to touch the gas line and then down to intersect with the other energy sources, one can determine the required percentages of each source to achieve a specific CO_2 emission threshold.

This graph provides decision-makers with valuable insights into the trade-offs between CO_2 emissions and the composition of the energy mix. It allows for informed decisions about adjusting the energy mix to meet environmental goals. For example, at CO_2 emission of 10 KT/MWhr, the net gas usage will be about 21.5% (0.215x(125-10) = 24.7MW). Overall hydro is 8% of the power generation (10/125=8%), overall wind is 19%, overall solar is 54% and that of gas is about 19%.

4.2 RESULTS OF NET GAS CO_2

Figure 4.2 was plotted using ***Table 4.1*** but in this case, Net gas CO_2 was plotted on the right y-axis instead of absolutes gas CO_2. ***Table 4.1*** provides a detailed breakdown of the net gas CO_2 emissions which is calculated by subtracting emissions from hydro, wind and solar from the overall gas CO_2 emissions.

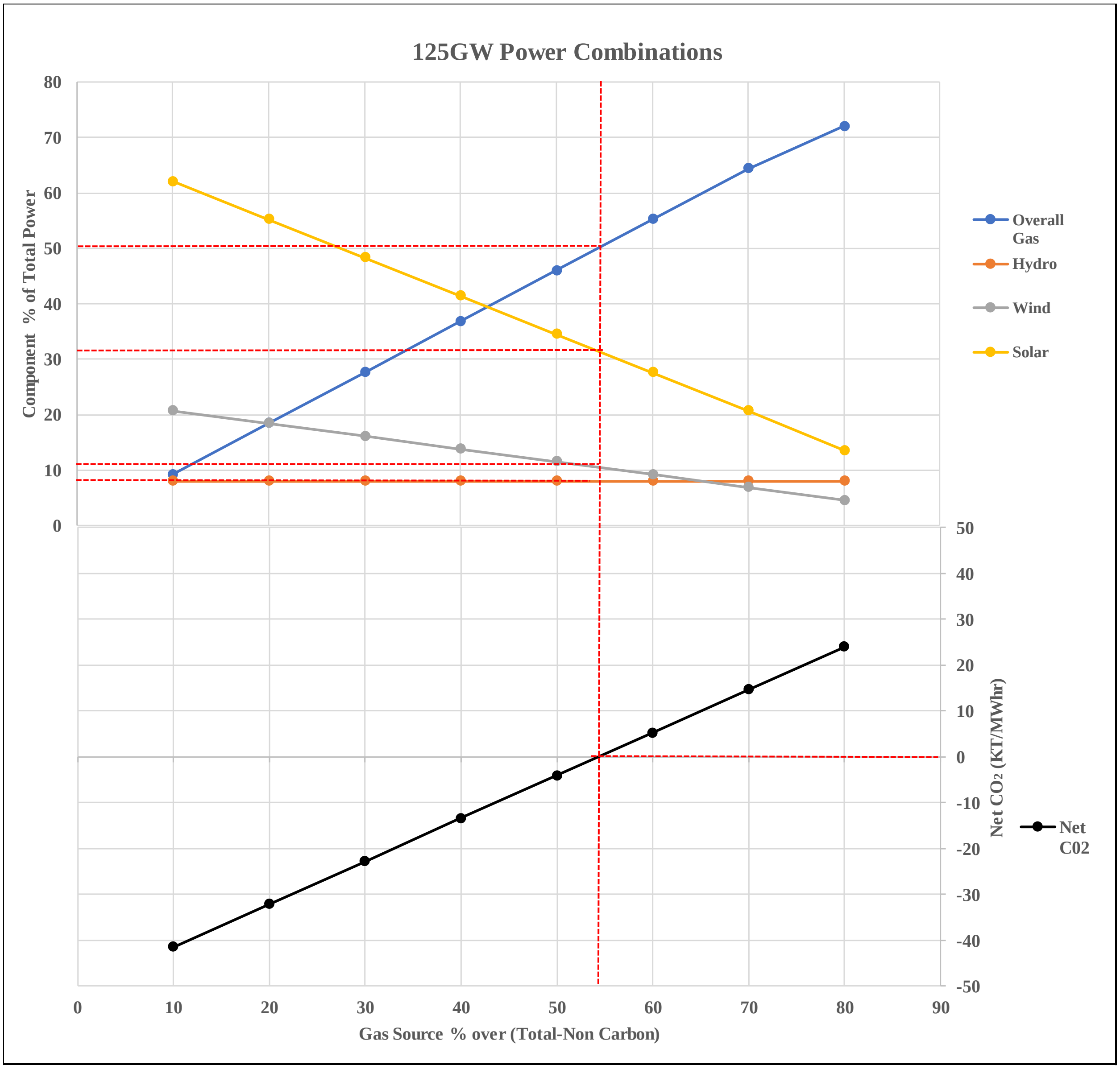

Figure 4.2: Net Gas CO_2 Analysis for 125GW of Power Generation

As expected, the net gas CO_2 emissions show a decreasing trend as the net gas percentage decreases. This indicates a shift towards a cleaner energy mix as the contribution of hydro and renewables (wind and solar) increases. Negative values in the net CO_2 axis indicate that, in these scenarios, the equivalent CO_2 emissions from hydro, wind and solar collectively offset the emissions from gas. This is a positive sign suggesting a potential for achieving a net reduction in carbon emissions. Observe that an inflection point occurs at 60% net gas. This is the point of transition at which the net CO_2 turns positive, implying that the combined equivalent emissions from hydro, wind and solar are no longer efficient to offset the emissions from gas. This inflection point could be critical for decision making as it may have implications that alter the trade-offs in terms of cost, reliability and emissions beyond this point.

To achieve net zero, one can simply trace a line through the point from the right y-axis as illustrated on the graph to the net gas line and then down to where it intersects the other energy sources. This is instrumental in determining the percentage composition of all the energy sources in the energy mix required to achieve net carbon zero. For example, when the net CO_2 emission is zero, the net gas percentage on x-axis is about 54% (0.54x(125-10) = 62.1MW). Overall gas is 50%, overall hydro is 8%, overall wind is 10% and overall solar 32%.

4.3 ENERGY MIX COST ESTIMATES

One primary objective of this energy mix model is to optimize the delicate balance between costs and CO_2 emissions. The goal is to identify the most cost-effective approach while concurrently minimizing carbon emissions.

The cost estimate graph, derived from ***Tables 4.3_1*** and ***Table 4.3_2***, serves as a pivotal tool in achieving this optimization. ***Table 4.3_1*** provides a detailed breakdown of the costs (measured in billion dollars) associated with electricity generation across varying demands, contingent upon a specified percentage of net gas. This cost breakdown encapsulates the total amount required for each energy combination.

Complementing this, ***Table 4.3_2*** offers a comprehensive breakdown of net carbon emissions associated with each energy demand, considering specific percentages of net gas. This nuanced analysis facilitates a holistic understanding of the environmental impact across different energy sources.

Table 4.3_1: Cost in Billion Dollars for Energy Generation Based on Net Gas Percentage

Cost ($B)								
Net Gas	**25GW**	**50GW**	**75GW**	**100GW**	**125GW**	**150GW**	**175GW**	**200GW**
0.00	57.05	93.68	130.30	166.90	203.60	240.20	276.80	313.50
10.00	55.80	90.34	124.90	159.40	194.00	228.50	263.10	297.60
20.00	54.54	87.00	119.50	151.90	184.40	216.80	249.30	281.70
30.00	53.29	83.66	114.00	144.40	174.80	205.10	235.50	265.90
40.00	52.04	80.32	108.60	136.90	165.20	193.40	221.70	250.00
50.00	50.78	76.98	103.20	129.40	155.50	181.70	207.90	234.10
60.00	49.53	73.63	97.70	121.80	145.90	170.00	194.10	218.20
70.00	48.28	70.29	92.31	114.30	136.30	158.40	180.40	202.40
80.00	47.03	66.95	86.88	106.80	126.70	146.70	166.60	186.50
100.00	44.52	60.27	76.02	91.77	107.50	123.30	139.00	154.80

Table 4.2_2: Net Carbon Emission for Energy Generation Based on Net Gas Percentage

Net CO2								
Net Gas	**25NETC**	**50NETC**	**75NETC**	**100NETC**	**125NETC**	**150NETC**	**175NETC**	**200NETC**
0.00	-10.18	-20.35	-30.53	-40.70	-50.88	-61.05	-71.23	-81.40
10.00	-8.95	-17.09	-25.23	-33.37	-41.51	-49.65	-57.79	-65.93
20.00	-7.73	-13.84	-19.94	-26.05	-32.15	-38.26	-44.36	-50.47
30.00	-6.51	-10.58	-14.65	-18.72	-22.79	-26.86	-30.93	-35.00
40.00	-5.29	-7.33	-9.36	-11.40	-13.43	-15.47	-17.50	-19.54
50.00	-4.07	-4.07	-4.07	-4.07	-4.07	-4.07	-4.07	-4.07
60.00	-2.85	-0.81	1.22	3.26	5.29	7.33	9.36	11.40
70.00	-1.63	2.44	6.51	10.58	14.65	18.72	22.99	26.86
80.00	-0.41	5.70	11.80	17.91	24.01	30.12	36.22	42.33
100.00	2.04	12.21	22.39	32.56	42.74	52.91	63.09	73.26

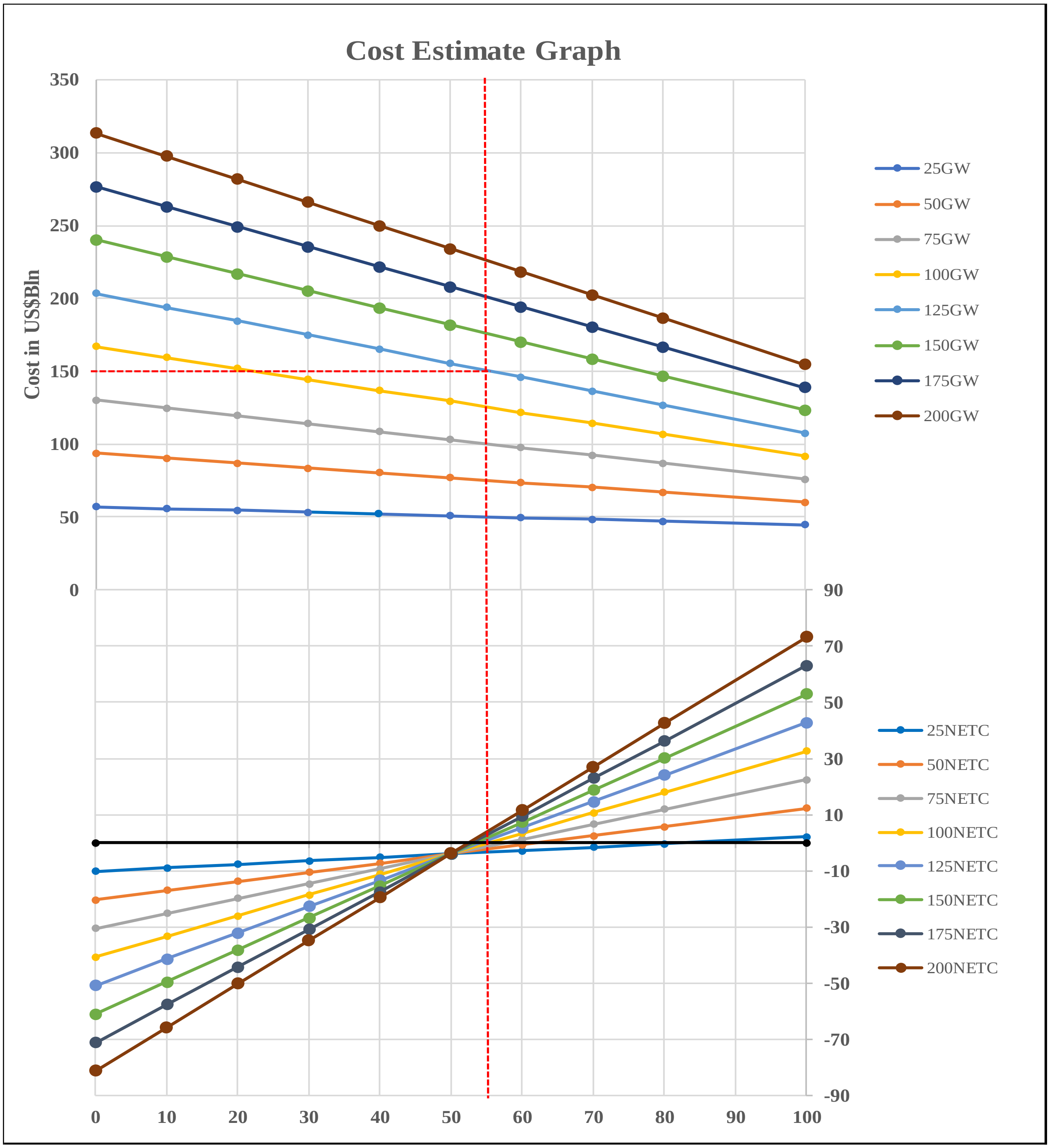

Figure 4.3: Energy Mix Cost-CO_2 Emission Estimate Graph

Figure 4.3 presents a comprehensive breakdown of cost estimates and associated net CO_2 emissions across varying net gas percentages and electricity generation capacities ranging from 25GW to 200GW. The graph features ascending CO_2 emission lines alongside descending cost lines, illustrating how an increase in net gas percentage leads to higher CO_2 emissions but reduced costs. To enhance clarity, the graph aligns CO_2 emission lines with corresponding colors of cost lines, simplifying the identification of costs at different CO_2 emission levels for diverse power generation demands.

Given that gas is notably more cost-effective than other considered energy sources, elevating the gas proportion in the energy mix results in cost reduction and a simultaneous increase in CO_2 emissions. The centrally positioned black line on the graph signifies net zero carbon emissions, indicating that for any energy demand, it is feasible to determine the energy source combination that achieves a net-zero carbon footprint. By tracing a line from the net zero line to the CO_2 line corresponding to a specific energy demand, and extending it to intersect with the cost line, the associated generation cost can be determined. This process is applicable for varying net carbon percentages ranging from -90 to 90 as shown on the graph, offering a comprehensive understanding of the trade-offs between cost and carbon emissions.

4.4 ENERGY MIX CO_2 ESTIMATES

The integration of renewable energy sources into the energy mix stands as a pivotal strategy for decarbonizing the power sector and attaining climate change objectives. ***Tables 4.4_1 and 4.4_2*** offer a detailed analysis essential for discerning the optimal Solar and Wind percentages necessary to achieve targeted net carbon emissions.

In ***Table 4.4_1***, a spectrum of solar + wind percentages are illustrated for each energy demand ranging from 25GW to 200GW, considering various net gas percentages. Complementing this, ***Table 4.4_2*** provides a detailed breakdown of net CO_2 emissions for each energy demand across diverse net gas percentages. These tables collectively furnish valuable insights into the attainable net carbon emissions achievable through the incorporation of solar and wind into the energy mix. This analytical framework offers a nuanced understanding of the interplay between solar, wind, and net carbon emissions, guiding informed decisions toward sustainable and low-emission energy solutions.

Table 3.4_1: Solar and wind percentage analysis

	Solar + Wind (%)							
Net Gas	**25GW**	**50GW**	**75GW**	**100GW**	**125GW**	**150GW**	**175GW**	**200GW**
0.00	60.00	80.00	86.70	90.00	92.00	93.30	94.30	95.00
10.00	54.00	72.00	78.00	81.00	82.80	84.00	84.90	85.50
20.00	48.00	64.00	69.30	72.00	73.60	74.70	75.40	76.00
30.00	42.00	56.00	60.70	63.00	64.40	65.30	66.00	66.50
40.00	36.00	48.00	52.00	54.00	55.20	56.00	56.60	57.00
50.00	30.00	40.00	43.30	45.00	46.00	46.70	47.10	47.50
60.00	24.00	32.00	34.70	36.00	36.80	37.30	37.70	38.00
70.00	18.00	24.00	26.00	27.00	27.60	28.00	28.30	28.50
80.00	12.00	16.00	17.30	18.00	18.40	18.70	18.90	19.00
100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 4.4_2: Net CO_2 emission by power generation capacity

	Net CO2							
Net Gas	25NETC	50NETC	75NETC	100NETC	125NETC	150NETC	175NETC	200NETC
0.00	-10.18	-20.35	-30.53	-40.70	-50.88	-61.05	-71.23	-81.40
10.00	-8.95	-17.09	-25.23	-33.37	-41.51	-49.65	-57.79	-65.93
20.00	-7.73	-13.84	-19.94	-26.05	-32.15	-38.26	-44.36	-50.47
30.00	-6.51	-10.58	-14.65	-18.72	-22.79	-26.86	-30.93	-35.00
40.00	-5.29	-7.33	-9.36	-11.40	-13.43	-15.47	-17.50	-19.54
50.00	-4.07	-4.07	-4.07	-4.07	-4.07	-4.07	-4.07	-4.07
60.00	-2.85	-0.81	1.22	3.26	5.29	7.33	9.36	11.40
70.00	-1.63	2.44	6.51	10.58	14.65	18.72	22.99	26.86
80.00	-0.41	5.70	11.80	17.91	24.01	30.12	36.22	42.33
100.00	2.04	12.21	22.39	32.56	42.74	52.91	63.09	73.26

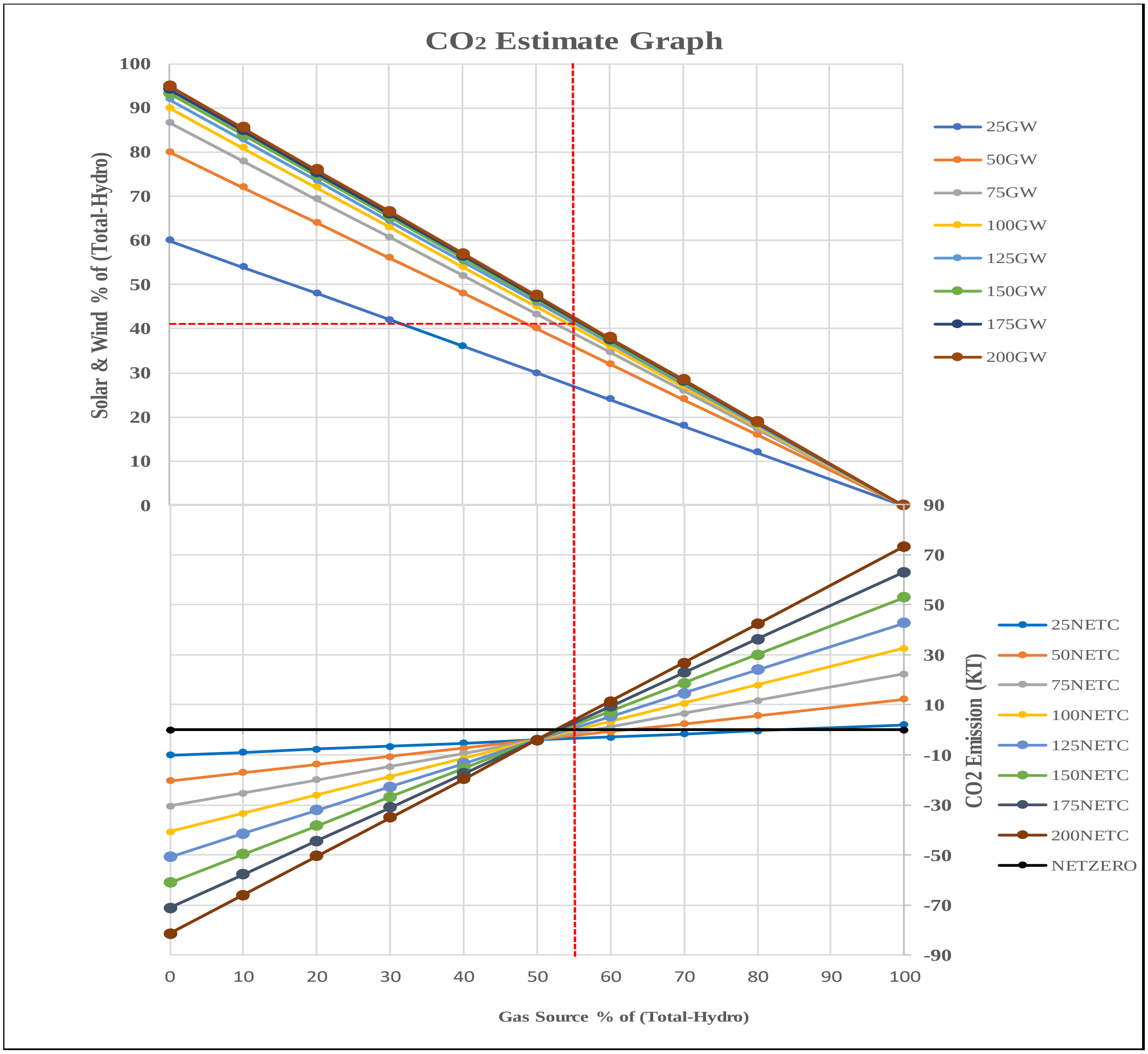

Figure 4.4: Energy Mix CO_2 Estimate

Building upon the insights derived from ***Tables 4.4_1 and 4.4_2***, ***Figure 4.4*** visually encapsulates the information, serving as a graphical representation of the CO_2 estimates within the energy mix. This illustration specifically focuses on the compositions of solar + wind at varying net gas percentages. The graph facilitates an understanding of the solar + wind percentages necessary to achieve a targeted CO_2 emission threshold corresponding to a specific energy demand. To enhance clarity, the CO_2 lines share the same color ratings as the solar + wind lines, ensuring proper alignment for seamless traceability.

The dynamic relationship between net gas percentage, solar + wind percentage, and CO_2 emissions is evident in the graph. With an increase in net gas percentage, the solar + wind percentage decreases, resulting in higher CO_2 emissions, and conversely, as the net gas percentage decreases, the solar + wind percentage rises, leading to reduced CO_2 emissions.

Central to the graph is the black line, illustrating the net carbon zero point — the juncture where carbon emissions are completely offset. This unique feature is achieved through calculations wherein the negative CO_2 emissions from renewables counterbalance the CO_2 emissions from gas. Tracing a line from the net zero CO_2 line to intersect with the solar + wind line facilitates the determination of the required solar + wind percentage to attain net zero carbon emissions. This principle holds true for all other presented CO_2 emission thresholds on the graph. The graph thus serves as a valuable tool for decision-making, offering a clear depiction of the intricate relationship between solar + wind compositions, net gas percentages, and carbon emissions.

4.5 DAILY GAS CONSUMPTION

Efficiently aligning energy generation with the varying demand throughout the day is crucial, particularly during peak demand periods. This necessitates a keen understanding of daily gas consumption patterns.

To facilitate this understanding, ***Table 4.5*** provides a detailed breakdown of daily gas consumption, encompassing both net and gross values. The net gas percentage represents the portion of power generation derived after deducting hydro capacity from the total power generation. In contrast, the gross gas percentage reflects the ratio between gas and total power generation without subtracting hydro capacity. This table serves as a valuable tool for analyzing the contributions of both net and gross gas consumption within the energy mix.

Table 4.5: Daily Gas consumption analysis (Net vs Gross)

Power (GW)	Cost ($B)	Daily Gas (Bscf/Day)	
		Gas is 50% Net	Gas is 50% Gross
25.00	0.30	1.51	2.52
50.00	0.40	4.03	5.04
75.00	0.43	6.55	7.56
100.00	0.45	9.08	10.08
125.00	0.46	11.60	12.61
150.00	0.47	14.13	15.13
175.00	0.47	16.62	17.65
200.00	0.48	19.16	20.17

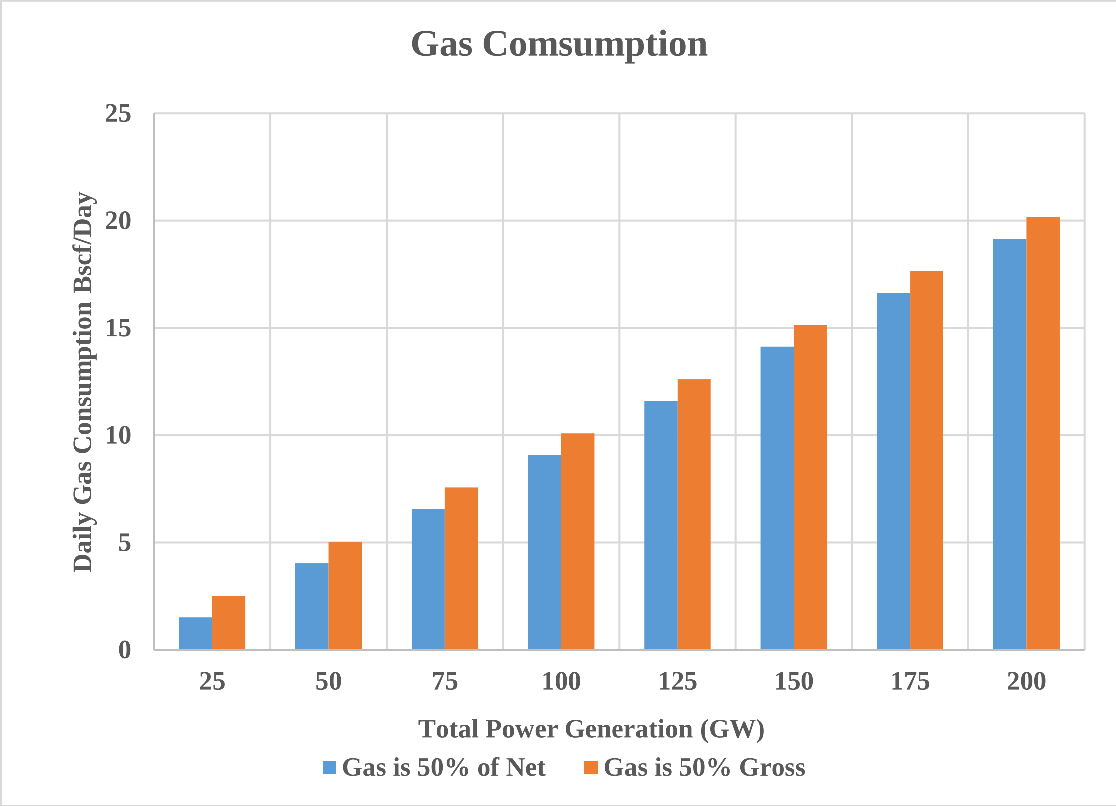

Figure 4.5: Daily Gas Consumption Analysis

This graph presents the daily gas consumption for different total electricity generation scenarios, considering both 50% net gas and 50% gross gas.

As the total electricity generation increases, the daily gas consumption also rises. This aligns with the higher energy demand requiring more gas to meet the power generation needs. The daily gas consumption is noticeably higher when gas constitutes 50% of the overall energy mix compared to when it is 50% of the net energy mix. This indicates the additional gas required to compensate for the intermittency of renewable sources in the overall energy mix.

Daily gas consumption analysis also allows for better operational planning, ensuring that the gas supply is sufficient to meet energy demands during peak hours without excessive waste during low-demand periods.

4.6 CUMULATIVE GAS CONSUMPTION – NET

The analysis of cumulative gas consumption offers valuable insights into the sustainability of Nigeria's gas reserves across diverse electricity generation scenarios. The examination was conducted based on the current estimated gas reserve for Nigeria, standing at approximately 181 trillion standard cubic feet (Tcf). The analysis utilizes this value as a threshold, visually represented by the black straight line on the chart in ***Figure 4.6***.

In ***Table 4.6***, the variables influencing cumulative gas consumption when gas is 50% of the net power generated are outlined. Considering that the lifespan of a gas plant is typically 30 years, the table is structured to reflect this lifecycle. Consequently, it provides a breakdown of cumulative gas consumption by year for each power generation demand, referencing the gas reserves value as a benchmark for comparison. This approach ensures a comprehensive understanding of the sustainability of gas reserves in the context of power generation capacities over time.

Table 4.6: Analysis of cumulative Gas consumption based on 50% of net

Year	25GW	50GW	75GW	100GW	125GW	150GW	175GW	200GW	Reserves (Tcf)
1	0.55	1.47	2.39	3.31	4.23	5.16	6.07	6.99	181
2	1.10	2.94	4.78	6.63	8.47	10.31	12.14	13.99	181
3	1.66	4.42	7.17	9.94	12.70	15.47	18.20	20.98	181
4	2.21	5.89	9.56	13.25	16.93	20.63	24.27	27.97	181
5	2.76	7.36	11.95	16.56	21.16	25.78	30.34	34.97	181
6	3.31	8.83	14.34	19.88	25.40	30.94	36.41	41.96	181
7	3.86	10.31	16.73	23.19	29.63	36.10	42.47	48.95	181
8	4.42	11.78	19.12	26.50	33.86	41.25	48.54	55.95	181
9	4.97	13.25	21.52	29.81	38.09	46.41	54.61	62.94	181
10	5.52	14.72	23.91	33.13	42.33	51.57	60.68	69.93	181
11	6.07	16.19	26.30	36.44	46.56	56.72	66.74	76.93	181
12	6.63	17.67	28.69	39.75	50.79	61.88	72.81	83.92	181
13	7.18	19.14	31.08	43.06	55.03	67.04	78.88	90.91	181
14	7.73	20.61	33.47	46.38	59.26	72.19	84.95	97.91	181
15	8.28	22.08	35.86	49.69	63.49	77.35	91.01	104.90	181
16	8.83	23.56	38.25	53.00	67.72	82.51	97.08	111.89	181
17	9.39	25.03	40.64	56.31	71.96	87.66	103.15	118.89	181
18	9.94	26.50	43.03	59.63	76.19	92.82	109.22	125.88	181
19	10.49	27.97	45.42	62.94	80.42	97.98	115.28	132.87	181
20	11.04	29.45	47.81	66.25	84.66	103.13	121.35	139.87	181
21	11.59	30.92	50.20	69.56	88.89	108.29	127.42	146.86	181
22	12.15	32.39	52.59	72.88	93.12	113.45	133.49	153.85	181
23	12.70	33.86	54.98	76.19	97.35	118.60	139.55	160.85	181
24	13.25	35.33	57.37	79.50	101.59	123.76	145.62	167.84	181
25	13.80	36.81	59.76	82.82	105.82	128.92	151.69	174.83	181
26	14.35	38.28	62.16	86.13	110.05	134.07	157.76	181.83	181
27	14.91	39.75	64.55	89.44	114.28	139.23	163.82	188.82	181
28	15.46	41.22	66.94	92.75	118.52	144.39	169.89	195.81	181
29	16.01	42.70	69.33	96.07	122.75	149.54	175.96	202.81	181
30	16.56	44.17	71.72	99.38	126.98	154.70	182.03	209.80	181

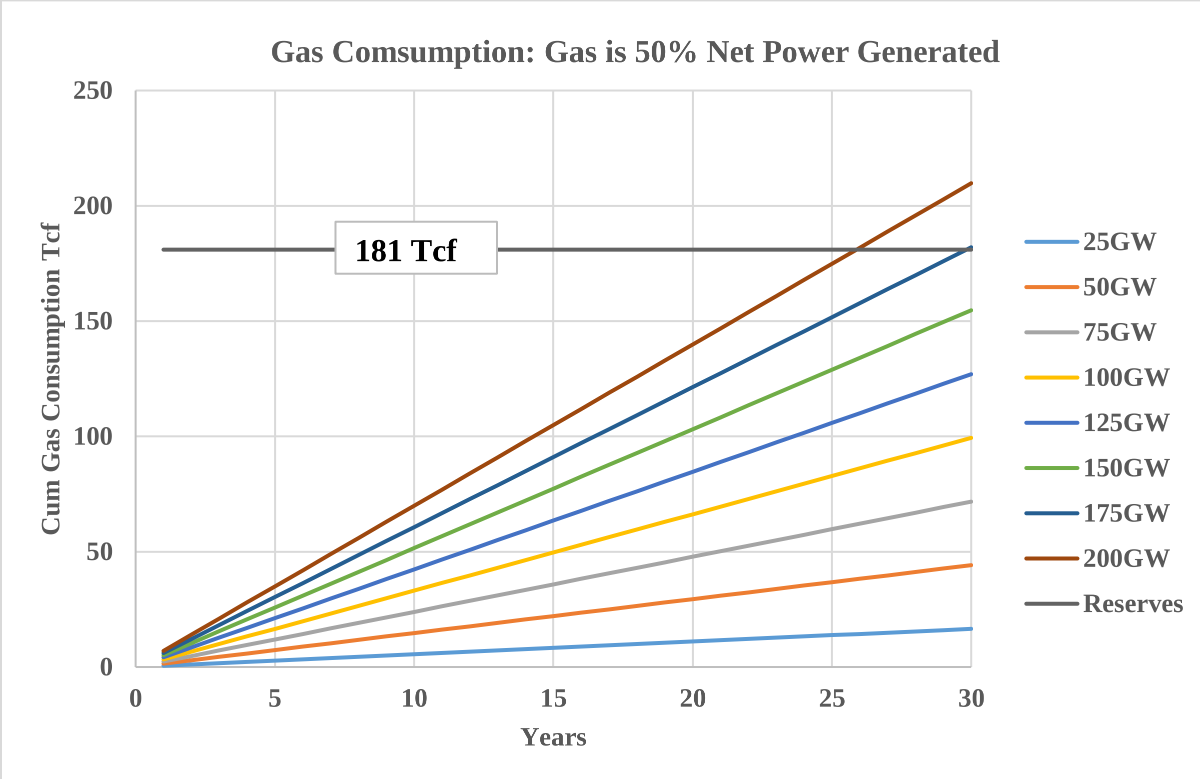

Figure 4.6: Cumulative Net Gas Consumption

The chart illustrates the cumulative net gas consumption over a 30-year period for various electricity generation capacities. As expected, higher electricity generation leads to faster depletion of gas reserves. Each line represents the cumulative gas consumption for each year based on the annual electricity generation scenario. For instance, if the country generates 175GW of electricity yearly from gas, the reserves would last approximately 30 years (see where the black line intersects).

The analysis emphasizes the importance of balancing electricity demands with gas reserves sustainability. Adjusting the electricity generation capacity allows for a sustainable use of gas resources over an extended period. Considering this chart based on 50% net power generation suggests that, with a balanced mix of energy sources, Nigeria can sustain a substantial portion of its electricity demand from gas while still preserving the longevity of its reserves. This balanced approach is crucial for ensuring energy security and environmental sustainability.

4.7 CUMULATIVE GAS CONSUMPTION – GROSS

After examining cumulative gas consumption based on 50% of the net power generated, it becomes imperative to turn our attention to cumulative gas consumption based on 50% of the total power generated. This significance arises from the fact that the gas reserve depletes at an accelerated pace when the energy mix incorporates the gross gas percentage.

In ***Table 4.7***, where 50% of the gross (total gas) is considered, a detailed breakdown of cumulative gross gas consumption over a 30-year period is presented. The corresponding chart in ***Figure 4.7*** enhances our understanding of this analysis, providing a visual representation of the cumulative gas consumption trends. This dual presentation in both table and chart formats contributes to a more comprehensive and insightful exploration of the implications associated with cumulative gas consumption (gross) in the energy mix.

Table 4.7: Analysis of cumulative Gas consumption based on 50% of net

Year	25GW	50GW	75GW	100GW	125GW	150GW	175GW	200GW	Reserves
1	0.92	1.84	2.76	3.68	4.60	5.52	6.44	7.36	181
2	1.84	3.68	5.52	7.36	9.20	11.04	12.88	14.72	181
3	2.76	5.52	8.28	11.04	13.80	16.56	19.32	22.08	181
4	3.68	7.36	11.04	14.72	18.40	22.08	25.76	29.45	181
5	4.60	9.20	13.80	18.40	23.00	27.61	32.21	36.81	181
6	5.52	11.04	16.56	22.08	27.61	33.13	38.65	44.17	181
7	6.44	12.88	19.32	25.76	32.21	38.65	45.09	51.53	181
8	7.36	14.72	22.08	29.45	36.81	44.17	51.53	58.89	181
9	8.28	16.56	24.84	33.13	41.41	49.69	57.97	66.25	181
10	9.20	18.40	27.61	36.81	46.01	55.21	64.41	73.61	181
11	10.12	20.24	30.37	40.49	50.61	60.73	70.85	80.97	181
12	11.04	22.08	33.13	44.17	55.21	66.25	77.29	88.34	181
13	11.96	23.92	35.89	47.85	59.81	71.77	83.74	95.70	181
14	12.88	25.76	38.65	51.53	64.41	77.29	90.18	103.06	181
15	13.80	27.61	41.41	55.21	69.01	82.82	96.62	110.42	181
16	14.72	29.45	44.17	58.89	73.61	88.34	103.06	117.78	181
17	15.64	31.29	46.93	62.57	78.21	93.86	109.50	125.14	181
18	16.56	33.13	49.69	66.25	82.82	99.38	115.94	132.50	181
19	17.48	34.97	52.45	69.93	87.42	104.90	122.38	139.87	181
20	18.40	36.81	55.21	73.61	92.02	110.42	128.82	147.23	181
21	19.32	38.65	57.97	77.29	96.62	115.94	135.26	154.59	181
22	20.24	40.49	60.73	80.97	101.22	121.46	141.71	161.95	181
23	21.16	42.33	63.49	84.66	105.82	126.98	148.15	169.31	181
24	22.08	44.17	66.25	88.34	110.42	132.50	154.59	176.67	181
25	23.00	46.01	69.01	92.02	115.02	138.03	161.03	184.03	181
26	23.92	47.85	71.77	95.70	119.62	143.55	167.47	191.39	181
27	24.84	49.69	74.53	99.38	124.22	149.07	173.91	198.76	181
28	25.76	51.53	77.29	103.06	128.82	154.59	180.35	206.12	181
29	26.68	53.37	80.05	106.74	133.42	160.11	186.79	213.48	181
30	27.61	55.21	82.82	110.42	138.03	165.63	193.24	220.84	181

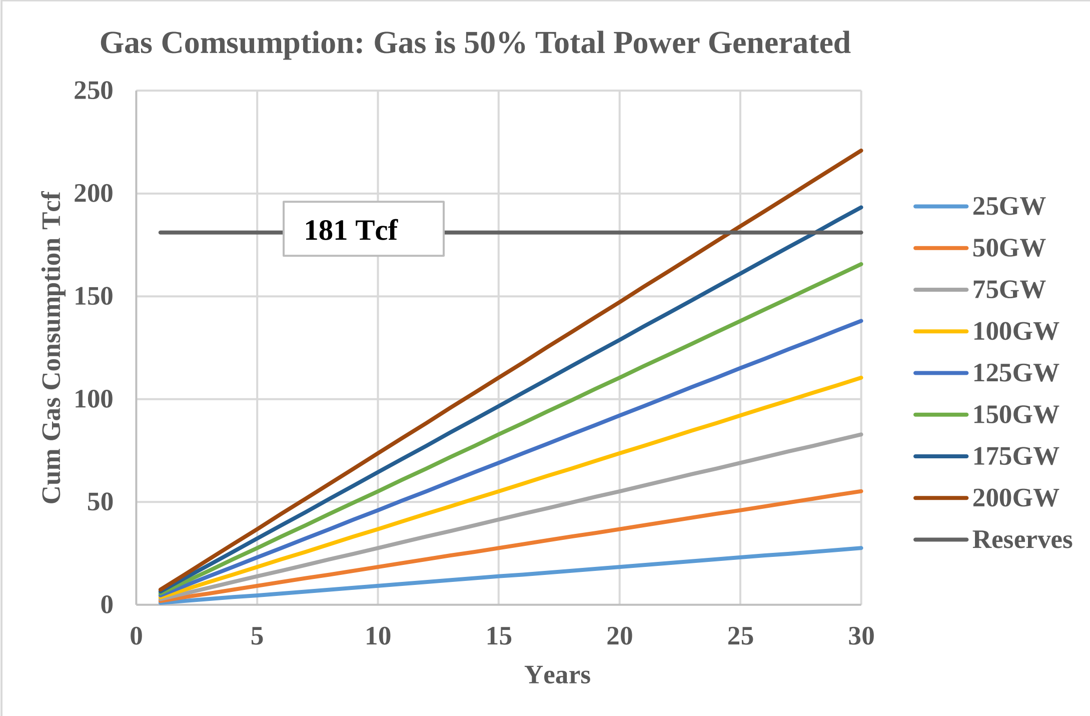

Figure 4.7: Cumulative Gross Gas Consumption

Optimizing the energy mix requires careful consideration of cumulative gas consumption, a pivotal variable crucial for modeling an energy strategy that preserves our gas reserves for the benefit of future generations.

In ***Figure 4.7***, this critical variable is visually represented, illustrating the accelerated depletion of gas reserves with increasing electricity generation. In contrast to ***Figure 4.6***, it becomes apparent that cumulative gas consumption, based on 50% of the total power generated, results in a more rapid gas consumption over time within the stipulated timeframe (30-years).

The implications of this analysis are significant. To ensure the sustainability of our gas reserves, the chart suggests that generating no more than 150GW with a 50% gross gas percentage is advisable. Beyond this threshold, there is a risk of depleting our gas reserves, necessitating the exploration of alternative electricity generation options. This structured approach to understanding cumulative gas consumption enhances our ability to make informed decisions for a sustainable and responsible energy future.

4.8 POWER GENERATION FROM GAS

In the Nigerian power generation landscape, gas claims the predominant share, comprising approximately 80% of the energy mix. Understanding the contribution of gas, both in net and gross terms, is instrumental for resource allocation. This comprehension empowers planners to make informed decisions regarding investments in gas infrastructure, extraction capabilities, and processing capacities, ensuring they align with the energy demands of the nation.

Gas assumes a pivotal role in supplying both baseload and peak power, contributing significantly to the stability of the power grid. This knowledge of gas power generation is indispensable for grid stability, guaranteeing a steadfast and reliable power supply, especially during periods of heightened demand.

For a nuanced analysis of the power generation from gas across various energy scenarios (ranging from 25GW to 200GW), ***Table 4.8*** delves into the specifics. The table meticulously breaks down the generation figures for each scenario, considering 50% of both net and gross electricity generation from gas. This detailed analysis offers insights into the dynamic contributions of gas across different energy generation capacities, providing a foundation for strategic planning and decision-making in the energy sector.

Table 4.8: Analysis of power generation from Gas (Net vs Gross)

Power (GW)	Cost ($B)	Power (GW)	
		Gas is 50% of Net	Gas is 50% Gross
25.00	0.30	7.50	12.50
50.00	0.40	20.00	25.00
75.00	0.43	32.48	37.50
100.00	0.45	45.00	50.00
125.00	0.46	57.50	62.50
150.00	0.47	70.05	75.00
175.00	0.47	82.43	87.50
200.00	0.48	95.00	100.00

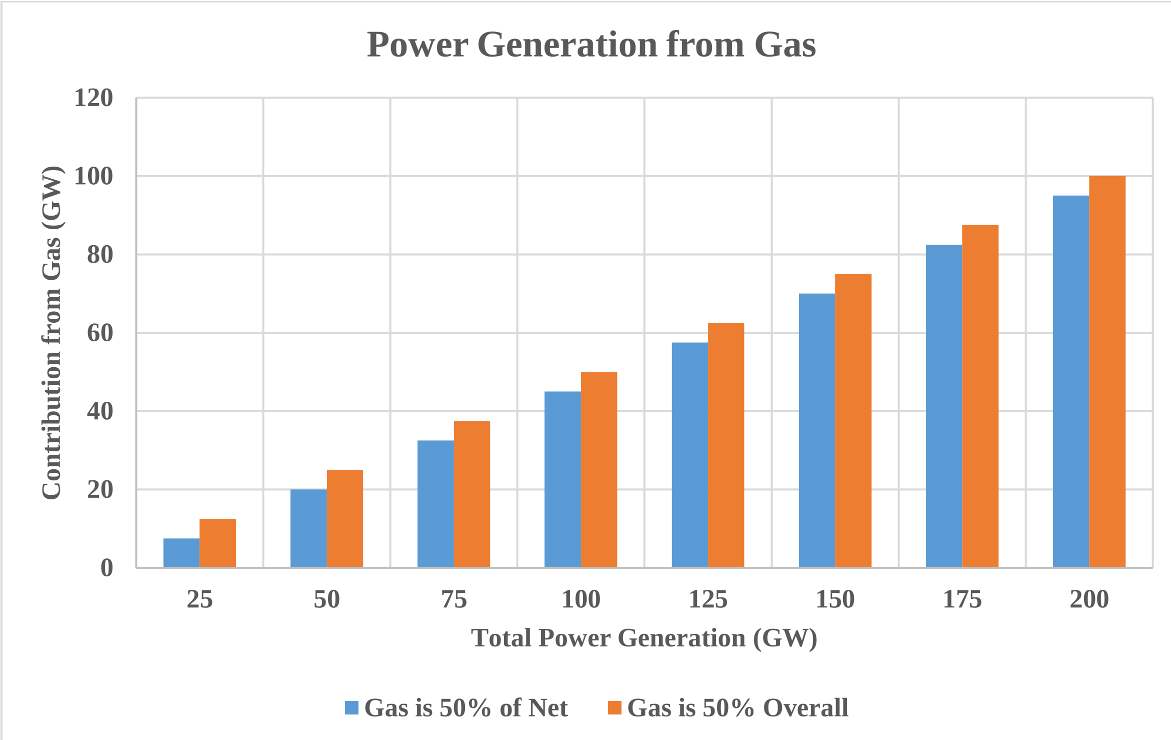

Figure 4.8: Power Generation Analysis

The presented bar chart ***(Figure 4.8)*** provides a visual depiction of power generation from gas across all electricity generation scenarios under consideration (25GW – 200GW). Within the chart, the blue bars signify electricity generation from gas, considering 50% of the net, while the orange bars represent the same, but based on 50% of the gross. As expected, the power generation from gas is naturally higher when evaluated in terms of gross generation compared to the net.

Moreover, the chart indicates a discernible upward trend in gas power generation. As the power generation capacity expands, there is a corresponding increase in the contribution from gas. This escalating trend underscores the growing significance of gas in meeting the expanding electricity demands.

4.9 PERCENTAGE POWER COMPONENT – NET ZERO

Examining the percentage components is instrumental in comprehending the contribution of each energy source within the energy mix, specifically in generating a designated electric power capacity, such as 100GW.

Table 4.9 provides a comprehensive breakdown of the variables utilized in constructing the chart presented in ***Figure 4.9***. Notably, this table delineates the percentage contribution by source for each energy generation capacity, ranging from 25GW to 200GW, based on 50% net gas. It's crucial to highlight that this specific table focuses solely on the basis of net carbon zero emissions. However, it is flexible and can be adjusted to reflect alternative combination requirements as needed.

Table 4.9. Percentage power component by source – Net zero

Net Zero Power Component					
Power GW	**% Wind**	**% Solar**	**% Hydro**	**% Gas**	**Total (%)**
25.00	2.50	7.50	40.00	50.00	100.00
50.00	7.50	22.50	20.00	50.00	100.00
75.00	9.20	27.50	13.30	50.00	100.00
100.00	10.00	30.00	10.00	50.00	100.00
125.00	10.50	31.50	8.00	50.00	100.00
150.00	10.80	32.50	6.70	50.00	100.00
175.00	11.10	33.20	5.70	50.00	100.00
200.00	11.25	33.75	5.00	50.00	100.00

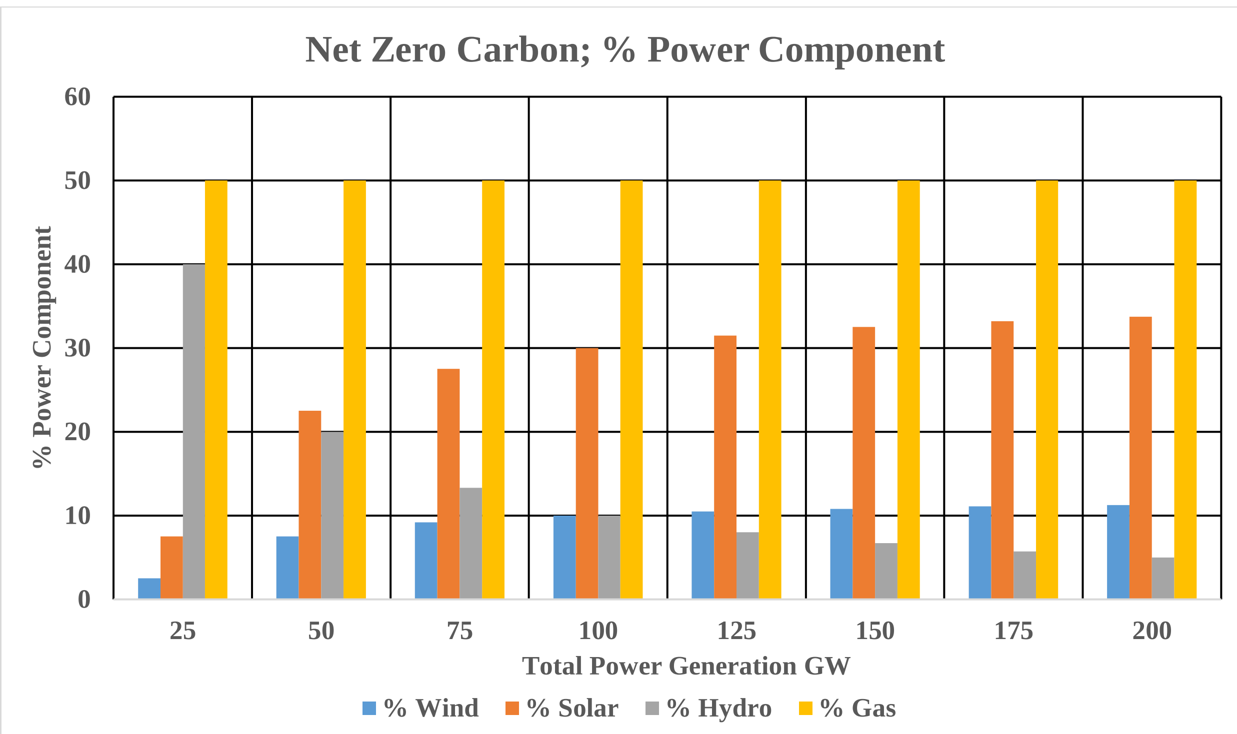

Figure 4.9: Percentage Power Component Analysis

Figure 4.9 visually presents the percentage component concerning net carbon zero, indicating the compositions of different energy sources required to achieve net carbon zero emissions for each energy generation capacity/demand. For example, to generate 75GW of electricity while keeping the gas percentage at 50% of net, a combination of approximately 9.2% wind, 27.5% solar, and 13.3% hydro would be necessary.

Conducting an analysis of the percentage component for net carbon zero is vital for aligning with environmental goals, informing policymaking, optimizing resource allocation, ensuring grid stability, promoting economic efficiency, and fostering technological innovation. It is an integral step toward achieving a sustainable and resilient energy future.

4.10 COST AND PERCENTAGE COMPONENT – NET ZERO

After examining the percentage composition of energy sources needed to attain net carbon zero for each energy generation capacity with 50% net gas, our focus now shifts to analyzing the associated costs for each combination.

Table 4.10 provides a comprehensive breakdown of costs associated with each component combination (gas, solar, wind, hydro) for every energy generation demand. This table meticulously dissects the total cost, delineating individual costs for each energy source based on the allocated percentage for electricity generation capacity.

The significance of this analysis lies in its ability to unveil the economic implications of achieving net carbon zero. By understanding the cost breakdowns for different energy source combinations, we gain insights into the financial considerations of adopting specific energy mixes. This information is vital for making informed decisions, optimizing resource allocation, and formulating cost-effective strategies in the pursuit of a sustainable and economically viable energy future.

Table 4.10: Cost and percentage component analysis

Net Zero Cost									
Total Cost ($B)	**Power (GW)**	**Wind Cost ($B)**	**% Wind**	**Solar Cost**	**% Solar**	**Hydro Cost**	**% Hydro**	**Gas Cost**	**% Gas**
46.61	25.00	1.80	3.86	1.87	4.00	35.07	75.24	7.88	16.90
72.80	50.00	10.79	14.82	11.19	15.37	35.07	48.17	15.75	21.63
98.99	75.00	19.77	19.97	20.52	20.73	35.07	35.43	23.62	23.86
125.20	100.00	28.76	22.97	29.85	23.84	35.07	28.01	31.50	25.16
151.40	125.00	37.75	24.93	39.18	25.88	35.07	23.16	39.38	26.01
177.60	150.00	46.77	26.33	48.54	27.33	35.07	19.75	47.22	26.59
203.80	175.00	55.73	27.35	57.84	28.38	35.07	17.21	55.12	27.05
229.90	200.00	64.71	28.15	67.16	29.21	35.07	15.25	63.00	27.40

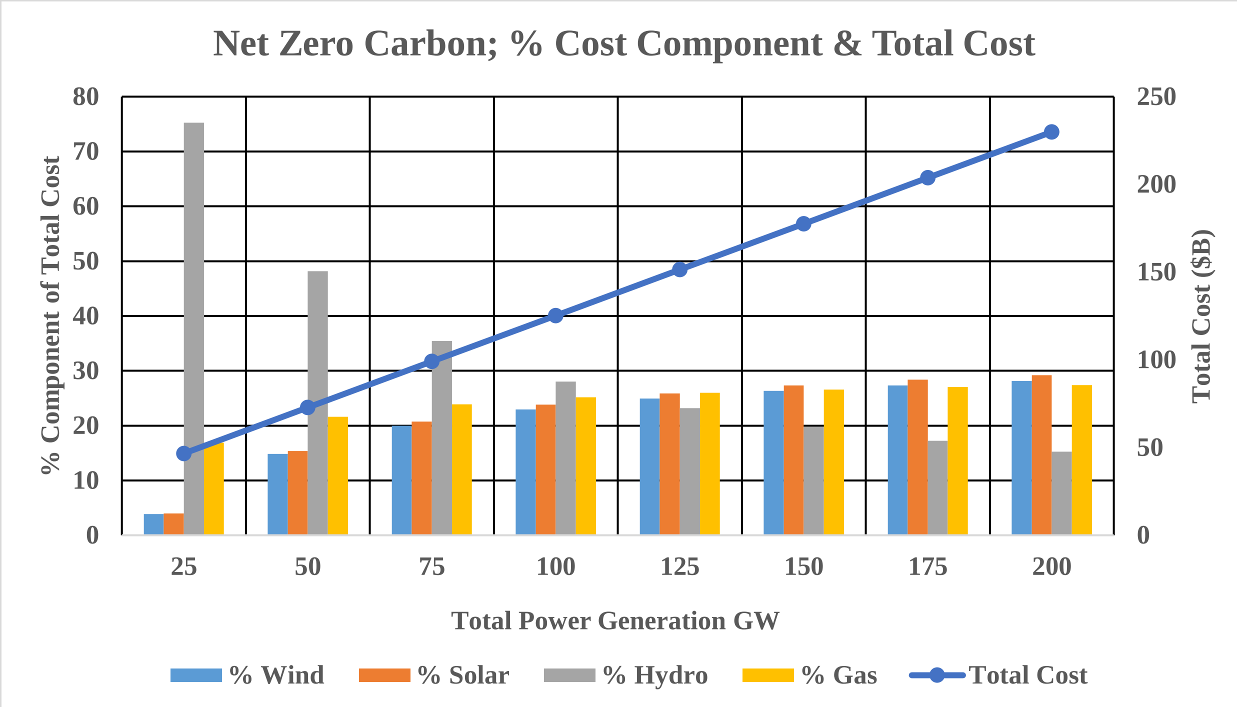

Figure 4.10: Cost and Percentage Component Analysis

The visual representation in ***Figure 4.10*** serves as a tool for determining the cost associated with each combination of energy sources (gas, hydro, solar, and wind) required to achieve net zero at varying energy demands. To extract the cost for each component, the chart is interpreted from left to right, revealing the percentage of the total cost attributed to each energy source. Calculating the actual total cost for each generation capacity within the range of 25GW to 200GW involves referencing the ascending blue line, indicating increasing costs as generation capacity rises.

This additional blue line, plotted on the chart, represents the total cost of electricity generation by capacity. The dots along this line signify the total cost corresponding to specific electricity generation capacities. Tracing these dots to the right side of the chart provides the total cost for each combination in billion dollars. Essentially, this entails aggregating the cost per generation for each source based on electricity generation capacity. This aggregation is achieved by multiplying the percentage component cost for each energy source by the total amount allocated for that generation capacity.

For instance, to calculate the total cost for generating 25GW, the equation would involve the summation of the products obtained by multiplying the percentage component cost for each energy source (3.86%, 4.00%, 75.24%, and 16.90% for wind, solar, hydro and gas respectively) by the total amount allocated for that generation capacity (46.61 billion dollars).

An interesting observation is the nearly equal cost from solar and wind, a result of the initially allocated ratio of 3:1 in the energy mix planning. This intricate analysis of costs per component is crucial in optimizing the energy mix, offering valuable insights into the economic implications of different combinations, and facilitating informed decision-making for a cost-effective and sustainable energy future.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

The conclusions derived from this thesis are presented in this section. Some recommendations are suggested for future research to improve the methodology and results obtained from this study.

5.0 CONCLUSIONS

Based on the comprehensive analysis presented in the optimization model, it is evident that the choice between net and gross gas generation significantly impacts various factors including cost, CO_2 emissions and gas consumption. The results presented in tables and graphs offer valuable insights into the different energy generation capacities for Nigeria.

The following conclusions can be derived from the result of this study:

- **Gas and Renewables Interaction:** The analysis highlights the interaction between gas and renewable sources (hydro, wind, solar) in shaping the overall energy mix. The choice of net gas percentage significantly influences the composition of the mix.
- **Energy mix sensitivity:** The energy mix is sensitive to changes in net gas percentages, showcasing a trade-off between cost-effectiveness and environmental impact.
- **Carbon emission dynamics:** The study provides a nuanced understanding of carbon emission dynamics. Depending on the gas percentage (net or gross), there are scenarios where renewables collectively contribute more to carbon reduction than gas alone.
- **Policy implications:** The findings have potential policy implications for energy planning in Nigeria. Decision makers can use this research to inform policies that balance economic considerations with environmental sustainability.
- **Decision support graphs:** The graphical representations with gas rating, absolute CO_2 emissions, net gas CO_2 emissions and gross percentage allows decision makers to visually assess the trade-offs and to determine the energy mix percentages to achieve specific CO_2 emission thresholds.
- **Inflection point identification:** There’s an inflection point around 60% net gas where the net CO_2 emissions for gas become positive, emphasizing the importance of considering different thresholds for optimizing the energy mix.
- **Scenario exploration:** The study provides a robust framework for exploring various scenarios, ranging from different total electricity generation levels to diverse net gas percentages. This flexibility allows for a comprehensive understanding of the implications

of different choices and how these can be adapted to suit various energy demands in the future.

This model appears to be a very simple model but in reality, it is a useful tool for all round analysis of the energy mix for power generation in Nigeria. This is because it can be tweaked for the purpose of achieving any given mix option. This is a valuable feature that allows for flexibility and adaptability of the model thereby enhancing the model's applicability to changing conditions. This adaptability is crucial for addressing dynamic factors in the energy landscape.

In general, to achieve an optimal energy mix for the Nigeria economy would require weighing the options on the scales referenced in Chapter 4 in order to decide based on the different metrics and combinations.

5.1 RECOMMENDATIONS

Based on the methodology and results of this study, the following recommendations are made; these recommendations aim to guide future decisions, ensuring a resilient and environmentally conscious energy infrastructure for Nigeria.

- **Fine-Tuning Cost-Emission Models:** Refine the cost-emission model to capture more nuanced scenarios, potentially incorporating external factors or uncertainties.
- **Sensitivity analysis:** Conduct sensitivity analysis to assess how variations in input parameters impact the model's outcomes, providing a more robust understanding of potential fluctuations.
- **Scenario Planning:** Extend the analysis to include scenario planning for unexpected events, policy changes or advancements in technology that may impact the energy landscape.
- **Collaboration with Environmental Experts:** Collaborate with environmental experts to further refine the CO_2 emission calculations and consider broader environmental impacts.
- **Policy Implications:** Investigate the policy implications of different power generation scenarios by aligning your findings with existing or proposed energy policies
- **Optimal Gas percentage:** Explore scenarios to identify an optimal net gas percentage that balances cost-effectiveness with environmental sustainability for each electricity generation capacity.
- **Renewable integration:** Investigate the integration of renewable sources to complement gas generation, aiming for a more balanced and sustainable energy mix.

- **Long-term planning:** Considering the finite gas, long-term planning should involve a transition towards renewable energy sources to ensure energy security beyond the lifespan of current gas reserves.
- **Continued analysis:** Conduct further analysis on the economic and environmental impact of integrating renewable sources, storage solutions, or advanced technology to enhance the overall energy system.
- **Stochastic model:** Adopt a stochastic approach which allows for the development of an energy strategy that accounts for the inherent uncertainties in Nigeria's energy system, leading to a more robust and resilient planning. This involves incorporating uncertainty and randomness into the model to better reflect the unpredictable nature of certain variables.

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APPENDIX

This Appendix shows additional results obtained from the methodology of this study. It explores the additional tables that were used to arrive at reasonable results for this study. This covers a wide range of energy generation scenarios for different percentages of energy sources.

NOTE: For each scenario, the variables stated below do not change

Hydro generation capacity = 10,000MW (10GW)

CO_2 rating = 0.407 Tonnes

Table A0: Cost per GW ($)

Primary Energy	**Cost per GW ($ 000,000)**		
	Low	**Average**	**High**
Gas	0.325	0.63	1.141
Hydro	0.996	3.507	7.484
Wind	1.721	2.876	4.039
Solar	0.534	0.995	2.006

APPENDIX A: ANALYSIS OF THE ENERGY MIX BASED ON 0% RENEWABLES

Table A4: 25GW Power generation based on 0% Renewables

Primary Energy	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
			Low	Average	High	
Gas	0.60	15.00	4.88	9.45	17.12	6.105
Hydro	0.40	10.00	9.96	35.07	74.84	4.07
Wind	0.00	0.00	0.00	0.00	0.00	0.00
Solar	0.00	0.00	0.00	0.00	0.00	0.00
Total	1.00	25.00	14.84	44.52	91.96	2.04

Table A2: 50GW Power generation based on 0% Renewables

Primary Energy	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
			Low	Average	High	
Gas	0.80	40.00	13.00	25.20	45.64	16.28
Hydro	0.20	10.00	9.96	35.07	74.84	4.07
Wind	0.00	0.00	0.00	0.00	0.00	0.00
Solar	0.00	0.00	0.00	0.00	0.00	0.00
Total	1.00	50.00	22.96	60.27	120.48	12.21

Table A3: 75GW Power generation based on 0% Renewables

Primary Energy	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
			Low	Average	High	
Gas	0.87	65.00	21.13	40.95	74.17	26.455
Hydro	0.13	10.00	9.96	35.07	74.84	4.07
Wind	0.00	0.00	0.00	0.00	0.00	0.00
Solar	0.00	0.00	0.00	0.00	0.00	0.00
Total	1.00	75.00	31.09	76.02	149.01	22.39

Table A4: 100GW Power generation based on 0% Renewables

Primary Energy	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
			Low	Average	High	
Gas	0.90	90.00	29.25	56.70	102.69	36.63
Hydro	0.10	10.00	9.96	35.07	74.84	4.07
Wind	0.00	0.00	0.00	0.00	0.00	0.00
Solar	0.00	0.00	0.00	0.00	0.00	0.00
Total	1.00	100.00	39.21	91.77	177.53	32.56

Table A5: 125GW Power generation based on 0% Renewables

Primary Energy	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
			Low	Average	High	
Gas	0.92	115.00	37.38	72.45	131.22	46.805
Hydro	0.08	10.00	9.96	35.07	74.84	4.07
Wind	0.00	0.00	0.00	0.00	0.00	0.00
Solar	0.00	0.00	0.00	0.00	0.00	0.00
Total	1.00	125.00	47.34	107.52	206.06	42.74

Table A6: 150GW Power generation based on 0% Renewables

Primary Energy	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
			Low	Average	High	
Gas	0.93	140.00	45.50	88.20	159.74	56.98
Hydro	0.07	10.00	9.96	35.07	74.84	4.07
Wind	0.00	0.00	0.00	0.00	0.00	0.00
Solar	0.00	0.00	0.00	0.00	0.00	0.00
Total	1.00	150.00	55.46	123.27	234.58	52.91

Table A7: 175GW Power generation based on 0% Renewables

Primary Energy	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
			Low	Average	High	
Gas	0.94	165.00	53.63	103.95	188.27	67.155
Hydro	0.06	10.00	9.96	35.07	74.84	4.07
Wind	0.00	0.00	0.00	0.00	0.00	0.00
Solar	0.00	0.00	0.00	0.00	0.00	0.00
Total	1.00	175.00	63.59	139.02	263.11	63.09

Table A8: 200GW Power generation based on 0% Renewables

Primary Energy	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
			Low	Average	High	
Gas	0.95	190.00	61.75	119.70	216.79	77.33
Hydro	0.05	10.00	9.96	35.07	74.84	4.07
Wind	0.00	0.00	0.00	0.00	0.00	0.00
Solar	0.00	0.00	0.00	0.00	0.00	0.00
Total	1.00	200.00	71.71	154.77	291.63	73.26

APPENDIX B: ANALYSIS OF THE ENERGY MIX BASED ON 0% GAS

Table 5: 25GW Power generation based on 0% Gas

Primary Energy	Gross Power Distribution (%)	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
				Low	Average	High	
Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydro	0.40	0.40	10.00	9.96	35.07	74.84	4.07
Wind	0.15	0.15	3.75	6.45	10.79	15.15	1.53
Solar	0.45	0.45	11.25	6.01	11.19	22.57	4.58
Total	1.00	1.00	25.00	22.42	57.05	112.55	-10.18

Table 6: 50GW Power generation based on 0% Gas

Primary Energy	Gross Power Distribution (%)	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
				Low	Average	High	
Gas	0.00	0.00	0.00	0.00	0.00	0.00	0
Hydro	0.20	0.20	10.00	9.96	35.07	74.84	4.07
Wind	0.20	0.20	10.00	17.21	28.76	40.39	4.07
Solar	0.60	0.60	30.00	16.02	29.85	60.18	12.21
Total	1.00	1.00	50.00	43.19	93.68	175.41	-20.35

Table 7: 75GW Power generation based on 0% Gas

Primary Energy	Gross Power Distribution (%)	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
				Low	Average	High	
Gas	0.00	0.000	0.00	0.00	0.00	0.00	0.00
Hydro	0.13	0.13	10.00	9.96	35.07	74.84	4.07
Wind	0.22	0.22	16.25	27.97	46.74	65.63	6.61
Solar	0.65	0.65	48.75	26.03	48.51	97.79	19.84
Total	1.00	1.00	75.00	63.96	130.31	238.27	-30.53

Table 8: 100GW Power generation based on 0% Gas

Primary Energy	Gross Power Distribution (%)	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
				Low	Average	High	
Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydro	0.10	0.10	10.00	9.96	35.07	74.84	4.07
Wind	0.22	0.22	22.50	38.72	64.71	90.88	9.16
Solar	0.68	0.68	67.50	36.05	67.16	135.41	27.47
Total	1.00	1.00	100.00	84.73	166.94	301.12	-40.70

Table 9: 125GW Power generation based on 0% Gas

Primary Energy	Gross Power Distribution (%)	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
				Low	Average	High	
Gas	0	0.00	0.00	0.00	0.00	0.00	0.00
Hydro	0.08	0.08	10.00	9.96	35.07	74.84	4.07
Wind	0.23	0.23	28.75	49.48	82.69	116.12	11.70
Solar	0.69	0.69	86.25	46.06	85.82	173.02	35.10
Total	1.00	1.00	125.00	105.50	203.57	363.98	-50.88

Table 10: 150GW Power generation based on 0% Gas

Primary Energy	Gross Power Distribution (%)	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
				Low	Average	High	
Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydro	0.07	0.07	10.00	9.96	35.07	74.84	4.07
Wind	0.23	0.23	35.00	60.24	100.66	141.37	14.25
Solar	0.70	0.70	105.00	56.07	104.48	210.63	42.74
Total	1.00	1.00	150.00	126.27	240.21	426.84	-61.05

Table 11: 175GW Power generation based on 0% Gas

Primary Energy	Gross Power Distribution (%)	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
				Low	Average	High	
Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydro	0.06	0.06	10.00	9.96	35.07	74.84	4.07
Wind	0.24	0.24	41.25	70.99	118.64	166.61	16.79
Solar	0.70	0.70	123.75	66.08	123.13	248.24	50.37
Total	1.00	1.00	175.00	147.03	276.84	489.69	-71.23

Table 12: 200GW Power generation based on 0% Gas

Primary Energy	Gross Power Distribution (%)	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
				Low	Average	High	
Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydro	0.05	0.05	10.00	9.96	35.07	74.84	4.07
Wind	0.24	0.24	47.50	81.75	136.61	191.85	19.33
Solar	0.71	0.71	142.50	76.10	141.79	285.86	57.99
Total	1.00	1.00	200.00	167.80	313.47	552.55	-81.40

APPENDIX C: ANALYSIS OF THE ENERGY MIX BASED ON NET CARBON ZERO

Table C1: 25GW Power generation based on net carbon zero

Primary Energy	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
			Low	Average	High	
Gas	0.50	12.50	4.06	7.88	14.26	5.09
Hydro	0.40	10.00	9.96	35.07	74.84	4.07
Wind	0.03	0.63	1.08	1.80	2.52	0.25
Solar	0.07	1.87	1.00	1.87	3.76	0.76
Total	1.00	25.00	16.10	46.61	95.39	0.00

Table C2: 50GW Power generation based on net carbon zero

Primary Energy	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
			Low	Average	High	
Gas	0.50	25.00	8.13	15.75	28.53	10.18
Hydro	0.20	10.00	9.96	35.07	74.84	4.07
Wind	0.08	3.75	6.45	10.79	15.15	1.53
Solar	0.22	11.25	6.01	11.19	22.57	4.58
Total	1.00	50.00	30.55	72.80	141.08	0.00

Table C3: 75GW Power generation based on net carbon zero

Primary Energy	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
			Low	Average	High	
Gas	0.50	37.50	12.19	23.62	42.79	15.26
Hydro	0.13	10.00	9.96	35.07	74.84	4.07
Wind	0.09	6.88	11.83	19.77	27.77	2.80
Solar	0.27	20.63	11.01	20.52	41.38	8.39
Total	1.00	75.00	44.99	98.99	186.77	0.00

Table C4: 100GW Power generation based on net carbon zero

Primary Energy	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
			Low	Average	High	
Gas	0.50	50.00	16.25	31.50	57.05	20.35
Hydro	0.10	10.00	9.96	35.07	74.84	4.07
Wind	0.10	10.00	17.21	28.76	40.39	4.07
Solar	0.30	30.00	16.02	29.85	60.18	12.21
Total	1.00	100.00	59.44	125.18	232.46	0.00

Table C5: 125GW Power generation based on net carbon zero

Primary Energy	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
			Low	Average	High	
Gas	0.50	62.50	20.31	39.38	71.31	25.44
Hydro	0.08	10.00	9.96	35.07	74.84	4.07
Wind	0.10	13.13	22.59	37.75	53.01	5.34
Solar	0.32	39.38	21.03	39.18	78.99	16.03
Total	1.00	125.00	73.89	151.37	278.15	0.00

Table C6: 150GW Power generation based on net carbon zero

Primary Energy	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
			Low	Average	High	
Gas	0.50	74.96	24.36	47.22	85.53	30.51
Hydro	0.07	10.00	9.96	35.07	74.84	4.07
Wind	0.11	16.26	27.98	46.77	65.68	6.62
Solar	0.32	48.78	26.05	48.54	97.86	19.85
Total	1.00	150.00	88.36	177.60	323.90	0.00

Table C7: 175GW Power generation based on net carbon zero

Primary Energy	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
			Low	Average	High	
Gas	0.50	87.50	28.44	55.12	99.83	35.61
Hydro	0.06	10.00	9.96	35.07	74.84	4.07
Wind	0.11	19.38	33.35	55.73	78.26	7.89
Solar	0.33	58.13	31.04	57.84	116.60	23.66
Total	1.00	175.00	102.78	203.76	369.54	0.00

Table C8: 200GW Power generation based on net carbon zero

Primary Energy	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
			Low	Average	High	
Gas	0.50	100.00	32.50	63.00	114.10	40.70
Hydro	0.05	10.00	9.96	35.07	74.84	4.07
Wind	0.11	22.50	38.72	64.71	90.88	9.16
Solar	0.34	67.50	36.05	67.16	135.41	27.47
Total	1.00	200.00	117.23	229.94	415.22	0.00

APPENDIX D: ANALYSIS OF THE ENERGY MIX BASED ON 20% NET GAS

Table D1: 25GW Power generation based on 20% net gas

Primary Energy	Gross Power Distribution (%)	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
				Low	Average	High	
Gas	0.12	0.20	3.00	0.98	1.89	3.42	1.22
Hydro	0.40	0.40	10.00	9.96	35.07	74.84	4.07
Wind	0.12	0.12	3.00	5.16	8.63	12.12	1.22
Solar	0.36	0.36	9.00	4.81	8.96	18.05	3.66
Total	1.00	1.08	25.00	20.90	54.54	108.43	-7.73

Table D2: 50GW Power generation based on 20% net gas

Primary Energy	Gross Power Distribution (%)	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
				Low	Average	High	
Gas	0.16	0.20	8.00	2.60	5.04	9.13	3.26
Hydro	0.2	0.20	10.00	9.96	35.07	74.84	4.07
Wind	0.16	0.16	8.00	13.77	23.01	32.31	3.26
Solar	0.48	0.48	24.00	12.82	23.88	48.14	9.77
Total	1.00	1.04	50.00	39.14	87.00	164.42	-13.84

Table D3: 75GW Power generation based on 20% net gas

Primary Energy	Gross Power Distribution (%)	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
				Low	Average	High	
Gas	0.17	0.20	13.00	4.23	8.19	14.83	5.29
Hydro	0.13	0.13	10.00	9.96	35.07	74.84	4.07
Wind	0.17	0.17	13.00	22.37	37.39	52.51	5.29
Solar	0.53	0.52	39.00	20.83	38.81	78.23	15.87
Total	1.00	1.027	75.00	57.38	119.45	220.41	-19.94

Table D13: 100GW Power generation based on 20% net gas

Primary Energy	Gross Power Distribution (%)	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
				Low	Average	High	
Gas	0.18	0.20	18.00	5.85	11.34	20.54	7.33
Hydro	0.10	0.10	10.00	9.96	35.07	74.84	4.07
Wind	0.18	0.18	18.00	30.98	51.77	72.70	7.33
Solar	0.54	0.54	54.00	28.84	53.73	108.32	21.98
Total	1.00	1.02	100.00	75.62	151.91	276.40	-26.05

Table D5: 125GW Power generation based on 20% net gas

Primary Energy	Gross Power Distribution (%)	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
				Low	Average	High	
Gas	0.18	0.20	23.00	7.48	14.49	26.24	9.36
Hydro	0.08	0.08	10.00	9.96	35.07	74.84	4.07
Wind	0.18	0.18	23.00	39.58	66.15	92.90	9.36
Solar	0.56	0.55	69.00	36.85	68.66	138.41	28.08
Total	1.00	1.01	125.00	93.86	184.36	332.39	-32.15

Table D6: 150GW Power generation based on 20% net gas

Primary Energy	Gross Power Distribution (%)	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
				Low	Average	High	
Gas	0.19	0.20	28.00	9.10	17.64	31.95	11.39
Hydro	0.07	0.07	10.00	9.96	35.07	74.84	4.07
Wind	0.18	0.19	28.00	48.19	80.53	113.09	11.39
Solar	0.56	0.56	84.00	44.86	83.58	168.50	34.18
Total	1.00	1.02	150.00	112.10	216.82	388.38	-38.25

Table D7: 175GW Power generation based on 20% net gas

Primary Energy	Gross Power Distribution (%)	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
				Low	Average	High	
Gas	0.19	0.20	33.00	10.73	20.79	37.65	13.43
Hydro	0.06	0.06	10.00	9.96	35.07	74.84	4.07
Wind	0.19	0.19	33.00	56.79	94.91	133.29	13.43
Solar	0.56	0.57	99.00	52.87	98.51	198.59	40.29
Total	1.00	1.01	175.00	130.34	249.27	444.37	-44.36

Table D8: 200GW Power generation based on 20% net gas

Primary Energy	Gross Power Distribution (%)	Net Power Distribution (%)	Electricity Generated by Source (GW)	Generation Cost ($ 000,000)			Carbon Emission by Source (KT)
				Low	Average	High	
Gas	0.10	0.20	20	6.50	12.60	22.82	8.14
Hydro	0.50	0.50	100	99.60	350.70	748.40	40.70
Wind	0.10	0.10	20	34.42	57.52	80.78	8.14
Solar	0.30	0.30	60	32.04	59.70	120.36	24.42
Total	1.00	1.10	200	172.56	480.52	972.36	-65.12

NOTE: These tables are not exhaustive of the analysis used for this study but only a representation of the total analysis as they illustrate the major categories for the analysis. However, the same analysis was conducted for the following ranges: 10% - 80% net gas and 50% gross gas.