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Pathways to environmental sustainability through energy efficiency: A strategic next energy vision for sustainable development by 2050

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A R T I C L E I N F O

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A B S T R A C T

As the global push for carbon neutrality accelerates, energy efficiency has become essential for sustainable development, especially for nations like Nigeria that face rising energy demands and significant environmental challenges. This study explores how integrating energy efficiency with carbon neutrality can support Nigeria's strategic energy goals while offering global lessons for other countries facing similar challenges, focusing on key sectors, including industry, transport, and power generation. The study systematically examines the impacts of renewable energy (RE) technologies, like solar, wind, and hydropower—alongside policy reforms, technological innovations, and demand-side management strategies to advance energy efficiency in Nigeria. Key findings include the identification of strategic policy frameworks, technological solutions, and the transformative role of green hydrogen in decarbonizing hard-to-electrify sectors. The study also emphasizes the importance of international climate finance, decentralized RE systems like solar mini-grids for improving energy access, and economic opportunities for job creation in the RE sector. Furthermore, it highlights the need for behavioral changes, community engagement, and consistent policy implementation to address infrastructure gaps and drive energy efficiency goals. The novelty of this research lies in its scenario-based analysis of Nigeria's low-carbon transition, detailing both the opportunities and challenges, such as policy inconsistencies, infrastructure deficits, and financial constraints. The findings stress the importance of international collaboration, technological advancements, and targeted investments to overcome these challenges. By offering actionable insights and strategic recommendations, this study provides a roadmap for policymakers, industry stakeholders, and researchers to drive Nigeria towards a sustainable, carbon-neutral future by 2050.

Introduction

As the world grapples with the pressing challenges of climate change (CC), energy efficiency and carbon neutrality (CN) have

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emerged as pivotal concepts in the global quest for sustainable development (SD). Energy efficiency (EE) refers to using less energy to achieve the same level of output or service, thereby reducing energy consumption and greenhouse gas emissions (GHGEs). On the other hand, CN represents a state where the net amount of carbon dioxide (CO_2) emitted into the atmosphere is balanced by an equivalent amount of carbon removal, either through natural or technological means. The significance of these concepts cannot be overstated, as it became necessary to incorporate low-carbon footprint objectives into the planning process to ensure reducing carbon emissions in an efficient manner [1]. In the face of escalating global temperatures, rising sea levels, and increasingly frequent extreme weather events, the international community has recognized the urgent need to transition towards more sustainable energy (SE) practices. This is reflected in global agreements such as the Paris Agreement, which seeks to limit global warming to well below 2°C, with efforts to restrict the increase to 1.5°C above pre-industrial levels. Reaching this ambitious goal demands unified action to improve EE across various sectors and take bold steps toward achieving CN [2]. Globally, actions to boost EE and attain CN are steadily advancing. Many countries have implemented policies and initiatives to reduce energy consumption, promote renewable energy sources (RESs), and develop innovative technologies to capture and store carbon emissions [3]. However, the pathway to a sustainable, carbon-neutral future is complex and challenging, especially for developing nations. The Federal Republic of Nigeria, with an estimated population of about 218 million people at a growth rate of around 2.53 %, is the most populous country in Africa and possesses the largest economy in terms of GDP [4,5]. It is projected that Nigeria will become the world's third most populous country by 2050, with a population of 480 million. In 2015, Nigeria's total final energy consumption (TFEC) was approximately 2.1 exajoules (EJ), equivalent to about 9 % of the TFEC in Africa. The energy sector in Nigeria is currently dominated by fossil fuels (FFs) and traditional biomass, which are significant sources of GHGEs. Diesel fuel possesses a Sulphur content of 3000 ppm (ppm), whereas gasoline exhibits a Sulphur content of 1000 ppm (ppm). The utilization of these fuels for powering generators has been associated with a mortality rate of 23.8 individuals per 1000 cases, surpassing the World Bank's regional average of 18.4 deaths per 1000 individuals for the African continent. Furthermore, businesses have documented instances of inventory loss attributed to fire incidents, the origins of which have been traced back to generator fuel utilization [6]. Nigeria has demonstrated its commitment to global efforts to combat CC, and its government is responsible for limiting national GHG emissions while pursuing sustainable development goals [7,8]. Urban green infrastructure holds significant importance in the context of sustainable urban development and societal well-being, particularly within swiftly urbanizing developing nations. Therefore, it becomes imperative to underscore that Nigeria's ongoing urbanization trends and patterns of physical development represent a pivotal juncture that demands thorough integration of informed insights about green infrastructure [9].

Carbon neutrality is crucial for Nigeria's SD as it aligns with global calls for decarbonization and promotes the transition to RESs, as highlighted in various studies [10]. By minimizing reliance on FFs, Nigeria can mitigate GHGEs, improve air quality, and foster economic diversification through job creation and developing a green economy [11]. Transitioning to carbon-neutral operations, such as adopting Sustainable Aviation Fuel (SAF) in the aviation industry, not only benefits the environment but also positions Nigeria as a regional leader in sustainable practices, contributing to long-term environmental sustainability and economic growth [12]. Embracing CN requires overcoming barriers like regulatory hurdles and inconsistent policies. Still, the shift towards renewable energy (RE) and low-carbon technologies is essential for Nigeria's future energy security and environmental resilience [13,14]. According to [13], Nigeria's ambition to reach net-zero carbon emissions may address the intertwined challenges of energy access, transition, and security. This could be achieved through supply-focused policies that realign the energy emission pathway with the 1.5-degree target while strategically leveraging fossil energy resources and RE to enhance power generation. Solar Creed puts the USD equivalent of Nigeria's levelized cost of solar electricity from PV systems within the range of 0.487 per kWh to 0.755 per kWh. Conversely, the USD equivalent for the levelized cost of diesel electricity is 2.368 per kWh, while that of gas is put at 1.397 per kWh. It is worth noting that households and businesses in Nigeria currently allocate more financial resources to fuel expenses than to the power generation sector, suggesting a potential upward trajectory in adopting alternative energy sources [15]. However, it is essential to acknowledge that the substantial initial investment costs still impede the widespread adoption of PV systems. The example of the Niger Delta region is non-negligible regarding enormous resources of oil, which shows an alternative way of fuel resource [16]; however, the area has also suffered from environmental, political, and developmental problems [17]. In light of recent changes in government leadership within the executive and legislative branches, the decision has been made to eliminate fuel subsidies. This shift has garnered substantial support from the populace regarding their Willingness to Pay (WTP) for seeking more cost-effective alternative energy sources. Low-carbon energy sources emerge as a practical and feasible alternative [6]. Consequently, a notable transformation occurs within the nation's energy landscape (ELS), necessitating concerted efforts to harness solar radiation (SR) into a viable power source. Contrary to the assertions put forth by [18] concerning the impact of oil prices on RE investments, it is pertinent to reference a report by [19], which underscores that fuel pricing is exerting a discernible influence on Nigerians' proclivity to embrace RE at a pace surpassing previous trends [18,20].

Recent global studies have highlighted novel strategies for attaining carbon neutrality (CN). Casey (2024) examined the roles of energy efficacy and guided technical change in mitigating climate change while Jung et al. (2024) identified transparent insulation systems as carbon-neutral design options for buildings [166,120]. Erker et al. (2022) demonstrated the macroeconomic benefits related to energy efficacy (EE) in building systems and Awad et al. (2024) provided an in-depth review of hydrogen production technologies to support energy-based decarbonization. These studies highlight the key roles of energy efficacy, renewable energy (RE), and green hydrogen in the world transitions to low-carbon societies [164,212].

The imperative is even greater in Nigeria with the nation's population growth rate, fossil fuel dependency, and exposure to climate change effects. Nigeria's Climate Change Act (2021) and Energy Transition Plan (NETP, 2022) established aggressive roadmaps to net-zero by 2060 and emphasize the imperative for implementable strategies in EE and RE deployment. Recent literature has already begun to tackle these issues. Lawal et al. (2024) estimated the environmental and economic benefits of household energy audits, and

Ochedi and Taki (2022) established a system design framework for energy-efficient households [153,154]. Adeyinka et al. (2024) investigated Nigeria's rising market for energy management systems, and Otobo et al. (2023) critically appraised the nation's electricity policies with implementation gaps identified [159,167].

Leaving aside these developments, however, the bulk of Nigerian analyses are sectoral ones dealing with households or buildings or individual policy scenarios. Few present an overall road mapping of EE, RE, and green hydrogen in an integrated CN route. This study fulfills that need by presenting a scenario analysis approach to consider Nigeria's energy transition in each key sector, namely industry, transport, and power generation segments, and incorporating needed policy reforms, technology innovation, and socio-economic parameters to reach CN by 2050.

This study aims to explore and compare various scenarios for low-carbon development in Nigeria, including potential threats and opportunities. Furthermore, to achieve the net-zero goal as per the Paris Agreement, we present a mission and vision by setting goals and strategic targets as well as policy implications and their safeguards for low-carbon energy transition in the Federal Republic of Nigeria [21]. Going further to x-ray the challenges and suggest ways to mitigate the risks is a plus for the energy sector. Given the renewed drive of Nigeria's government to resuscitate the power sector, its recent enactment of the power bill, and the minister's inauguration for power. We believe this research will make a meaningful contribution to Nigeria's low-carbon development policies and engage critical stakeholders in the country in the debate over SE transition [22,23].

Motivations of the study

The urgent need for SE solutions drives the global transition toward CN, particularly as climate change intensifies. Countries like Nigeria, with a growing population and heavy reliance on fossil fuels, are at a critical juncture where EE must be integrated with carbon reduction strategies to foster sustainable development. This study is motivated by the realization that achieving carbon neutrality by 2050 requires a profound transformation in Nigeria's energy landscape, including adopting RESs, improving EE, and developing innovative technologies like green hydrogen.

The motivation for this research also stems from the increasing pressure on developing countries to align with international climate agreements, such as the Paris Agreement, while addressing local socio-economic challenges. As Africa's largest economy, Nigeria faces unique obstacles, such as policy inconsistencies, infrastructure gaps, and financial barriers, which hinder its transition toward a low-carbon economy. By investigating the intersection of EE and carbon neutrality, this study aims to offer strategic insights that can help overcome these barriers and unlock Nigeria's potential for sustainable growth. Despite its significant promise, the transformative potential of green hydrogen (GH) as a clean energy solution has not been fully explored in the Nigerian context. This research is further motivated by the need to assess how Nigeria can leverage its abundant RE resources to develop a sustainable hydrogen supply chain, which could be crucial in decarbonizing vital sectors such as transportation and industry.

Purpose and objectives of the study

The primary purpose of this study is to provide a comprehensive analysis of how EE can be integrated with carbon neutrality to achieve SD, particularly in the context of Nigeria. This research aims to explore the synergies between EE measures and carbon reduction strategies, offering a strategic framework for transitioning toward a carbon-neutral society by 2050. The study identifies the key factors driving this transition by examining global trends, successful case studies, and Nigeria's unique socio-economic and environmental challenges. The objectives of this study are threefold:

1. To evaluate the impact of EE and RE adoption on Nigeria's ability to achieve carbon neutrality, focusing on critical sectors such as industry, transportation, and power generation.
2. To analyze the strategic approaches and policies necessary for Nigeria to meet its 2050 carbon-neutral goals, particularly overcoming infrastructure, policy, and financial barriers.
3. To assess the transformative potential of the green hydrogen supply chain as a clean energy solution for Nigeria, exploring how hydrogen technologies can decarbonize hard-to-electrify sectors and support sustainable energy objectives.

In addressing these objectives, the study explores several vital questions:

(a) How can EE measures accelerate Nigeria's transition to carbon neutrality and support global efforts toward climate change mitigation?
(b) What are the most effective policy strategies for integrating EE with Nigeria's broader energy goals, and how can these strategies be adapted to overcome current challenges?
(c) How can Nigeria leverage its RE resources to develop a GH supply chain that supports long-term sustainability and energy security?

Research gap and novelty of the study

While numerous studies have investigated energy efficiency, renewable energy adoption, or hydrogen development in isolation, the majority of Nigerian-focused analyses remain sector-specific, examining households, buildings, or individual policy frameworks without providing an integrated roadmap. Few studies combine global insights with Nigeria's unique socio-economic realities to present a comprehensive strategy for carbon neutrality by 2050.

The novelty of this study lies in its integrated approach, which:

1. Consolidates energy efficiency, renewable energy, and green hydrogen into a unified framework for Nigeria's carbon neutrality transition through presenting a scenario analysis approach.
2. Bridges global best practices with Nigeria's policy, infrastructure, and socio-economic context.
3. Proposes a mission, vision, and strategic policy safeguards across multiple sectors (power, industry, transport, buildings, and agriculture) to guide a holistic transition pathway.

By addressing these research gaps, the paper advances a comprehensive perspective that goes beyond fragmented sectoral studies, offering policymakers and stakeholders a clear roadmap for achieving sustainable, carbon-neutral development in Nigeria by 2050.

Paper organization

This paper is structured into nine main sections. Section 1 introduces the study, outlining the motivation, purpose, objectives and research gap. Section 2 describes the methodology and analysis, including data sources, screening criteria, and relevance of Nigeria as a case study. Section 3 reviews global approaches to achieving carbon neutrality by 2050, covering strategies, policy frameworks, technological innovations, behavioral aspects, and the pivotal role of clean energy. Section 4 examines Nigeria's pathway to carbon

Fig. 1. Visual Hierarchical Structure of the Proposed Study.

neutrality, discussing its energy landscape, national policies, challenges, opportunities, case studies, and the potential impacts of transition. Section 5 focuses on the role of energy efficiency in achieving carbon neutrality, integrating global insights with Nigeria's context. It addresses innovations, case studies, strategic integration, mission and vision, and policy safeguards across key sectors. Section 6 explores the potential of a green hydrogen supply chain in Nigeria, highlighting policies, international collaboration, pilot projects, opportunities, and challenges. Section 7 presents the limitations and scope of the study. Section 8 provides the conclusion, academic contribution, summarizing findings, and their implications. Finally, Section 9 offers recommendations for future research, identifying pathways to advance Nigeria's sustainable, low-carbon development by 2050. To further improve clarity, Fig. 1 provides a visual roadmap of the whole manuscript's structure. This figure illustrates the hierarchical organization of sections and subsections, helping readers quickly grasp the flow of the study and navigate its content more effectively.

Methodology and analysis

This paper employs a comprehensive review of secondary literature, academic journal articles, and papers from academic conferences to analyze Nigeria's EE policies and carbon neutrality strategies. The research methodology involved an extensive search of scholarly databases, including "Google Scholar," "Web of Science (WoS)," "Scopus," and "JSTOR," using specific keywords including "energy efficiency," "carbon neutrality," and "Nigeria." The aim was to gather relevant research articles, conference papers, policy documents, and case studies that address Nigeria's energy transition toward sustainable development by 2050.

For academic publications, 331 research articles were initially retrieved through keyword searches in the abovementioned databases. The keywords "energy efficiency" OR "carbon neutrality" AND "Nigeria" were used to refine the search, ensuring that the focus remained on Nigeria's energy policy landscape. Articles that were not directly related to Nigeria or that lacked specific discussions on energy efficiency and carbon neutrality were excluded from the final selection. Articles and conference papers published before 2015 were excluded to ensure that the analysis reflected the most up-to-date strategies, particularly in light of Nigeria's commitments under the Paris Agreement and its Energy Transition Plan. After screening for relevance and recency, 191 original research articles and conference papers were identified as suitable for further analysis. The analysis also incorporated industry reports, government publications, and international agency documents to provide a broader context. For this, Google's search engine was utilized with keywords such as "Nigeria energy policy," "Nigeria carbon neutrality strategy," "Nigeria leadership role for the African region," and "RE Nigeria." Sixty reports from industry and government, non-government organization (NGO) reports, information, and reports from different media outlets, and international energy organizations were reviewed, ensuring that the data covered the policy framework and the technical aspects of EE and carbon neutrality in Nigeria. The data from these sources were systematically compiled to address the key research questions of this paper. How can EE be integrated into Nigeria's carbon neutrality goals by 2050? What are the significant challenges and opportunities in implementing EE policies across critical sectors such as industry, transportation, and power generation? Aforementioned, we primarily adopt a systematic literature review approach, synthesizing peer-reviewed articles, policy reports, and international databases. In addition, secondary quantitative data and established modeling frameworks from the literature (e.g., carbon tax formulas, sectoral emission statistics) are integrated to illustrate global and national pathways toward carbon neutrality. These illustrations are not original empirical simulations but evidence-based representations derived from prior studies. This analysis highlights successful case studies and the barriers that must be addressed, including policy inconsistencies, infrastructure deficits, and investment gaps. The findings were synthesized to propose actionable strategies for accelerating Nigeria's energy transition toward a sustainable, carbon-neutral future.

Relevance of Nigeria as a case study

As one of Africa's largest economies and a major oil producer, Nigeria presents a unique case study for exploring the challenges and opportunities of transitioning to a carbon-neutral future. The country's ELS is characterized by a heavy reliance on FFs, particularly oil and gas, which have historically contributed significantly to its economy [24]. However, this reliance on FFs also makes Nigeria vulnerable to the economic and environmental risks associated with global decarbonizing efforts. At the same time, Nigeria holds substantial potential for RE, especially in solar and hydroelectric power, which could be harnessed to support its transition towards carbon neutrality [25]. By examining Nigeria's current energy policies, clean energy initiatives, and potential for hydrogen development, this paper provides insights into how developing countries can navigate the complexities of achieving EE and carbon neutrality.

Global approaches to carbon-neutral society by 2050

Global strategies and policy frameworks

Achieving global carbon neutrality by 2050 has become a central research and policy agenda, requiring coordinated international efforts that integrate robust policy frameworks, technological innovation, and socio-economic adaptation. The Paris Agreement provides the foundation for these efforts, setting a legally binding framework to limit global temperature rise to well below 2°C, with an aspiration toward 1.5°C, yet a significant gap remains between current Nationally Determined Contributions (NDCs) and the reductions needed to meet these targets [26]. In response, various regions have adopted comprehensive strategies; for example, the European Green Deal outlines a pathway to climate neutrality by 2050 through measures such as raising the renewable energy share to 40 % by 2030, implementing a carbon border adjustment mechanism, and advancing a circular economy, further reinforced by the

European Climate Law that mandates policy alignment with long-term climate goals [27]. Similarly, Japan's Green Growth Strategy emphasizes renewable expansion, energy efficiency, and hydrogen development across 14 key sectors [28], while South Korea has committed to phasing out coal and accelerating renewable adoption to achieve net-zero emissions by 2050 [29]. In North America, Canada's Net-Zero Emissions Accountability Act legally binds the 2050 neutrality target and is supported by CAD 15 billion in investments toward clean energy and resilience projects [30]. Beyond national policies, global cooperation mechanisms such as the Clean Energy Ministerial and Mission Innovation foster cross-border collaboration and innovation in clean technologies [31].

Table 1
Some selected global trends in carbon neutrality.

No.	Ref.	Country	Work done and Target year	Lessons learned
1	[32]	Nepal	Nepal's energy strategy focuses on EE, security, and affordability by 2030, hydropower and solar energy (SE) by 2050, and carbon neutrality by 2100. Target year: 2100	Need to support, enforce, incentivize, and promote policies for sustainable development to meet Paris Agreement targets.
2	[33]	China	Analyzes sustainable development of China's new energy industry, focusing on energy conservation and emission reduction in the building industry. Target year: 2030, 2050	Goal decomposition and integration of energy conservation and emission mitigation strategies are critical for reducing environmental pollution and energy waste.
3	[34]	Thailand	It uses STEEP analysis to identify influential factors for achieving carbon neutrality by 2050 and explores two scenarios (Classic and Orchestra) for the energy sector. Target year: 2050	Importance of political will, green technology, financial incentives, and holistic management in achieving carbon neutrality.
4	[35]	Pakistan	Investigates relationships between electricity consumption, renewable electricity output, energy use, and CO_2 emissions in Pakistan. Target year: 1990–2017	Enhance RE use and introduce policies to mitigate CO_2 emissions to resolve the energy crisis.
5	[40]	Argentina	Examines the impact of renewable electricity generation, economic globalization, economic growth, and urbanization on CO_2 emissions in Argentina. Target year: 1971–2016	Renewable electricity generation can curb emissions; economic globalization and urbanization can boost them. Policies should focus on controlling energy production-based emissions.
6	[36]	Argentina	Evaluate the impacts of renewable electricity output, trade globalization, economic growth, financial development, urbanization, and technological innovation in Argentina. Target year: 2050	Promoting RE, sustainable economic growth, and technological innovation are crucial to decarbonizing the economy.
6	[37]	Japan	Assesses the impact of government investments in clean energy research and development on Japan's carbon dioxide emissions. Target year: 2050	Scaling up investments in clean energy and sustainable urbanization is crucial for long-term emission reduction.
7	[38]	Finland	Explores carbon-neutral city concept, focusing on definition, assessment strategies, and barriers to transition. Target year: 2030	Harmonization and guidance on standard assessment approaches are needed to support cities in achieving carbon neutrality.
8	[39, 40]	China	Details China's plan to reach peak carbon emissions by 2030 and attain net-zero emissions by 2060 Target year: 2060	Importance of energy transformation, emission control, and development of carbon trading markets and public awareness for green economic growth.
9	[41]	USA	Assesses the role of eco-innovation and globalization in mitigating CO_2 emissions using the Quantile Autoregressive Distributed Lag (QARDL) approach. Target year: NA	GDP positively influences CO2 emissions, but GDP square negatively impacts them, supporting EKC. Eco-innovation mitigates, while globalization stimulates CO2 emissions. Policymakers should focus on eco-innovation.
10	[42]	South Africa	Examines the effect of conventional energy usage, agricultural practices, and economic growth on environmental sustainability and explores RE and technological innovation Target year: 1975–2020	Economic growth, FF energy consumption, and agricultural activities adversely affect environmental sustainability. RE and technological innovation positively influence ecological quality.
11	[43]	USA	Investigate the role of green growth, globalization, and RE consumption in limiting CO_2 emissions. Target year: 1990–2019	Green growth, RE, and globalization are key factors affecting CO2 emissions. A downward adjustment of economic growth is necessary to achieve carbon neutrality.
12	[44]	EU	Reviews EU City-zen project roadshows for planning and kick-starting energy transitions- and climate-neutral economies in cities. Target year: 2050	Participatory processes and multi-stakeholder engagement effectively identify decarbonization pathways and visualize future sustainable cities.
13	[45]	USA and China	Compares national paths and policies to achieve CN and analyses stage impacts of carbon emission minimization. Target year: NA	The USA follows a "Bottom to Top" system and is in the absolute carbon emission minimization period. In contrast, China follows a "Top to Bottom" system and is in the relative carbon emission minimization period. China faces a shorter transition period.
14	[46]	Brazil, Russia, India, China, and South Africa	Evaluate the benefits of fiscal decentralization, export diversification, and environmental and technological innovation in meeting environmental sustainability goals. Target year: 1970–2020	While environmental, technological innovation and RE benefit the environment, export diversification, fiscal decentralization, and economic growth exacerbate ecological deterioration. Governments should promote ERTI and REC.

Collectively, these frameworks underscore that while significant progress has been made, bridging the ambition gap toward mid-century carbon neutrality will require more aggressive policy commitments, sustained innovation, and enhanced international cooperation as detailed in Table 1.

Technological innovations driving the transition

The transition to a carbon-neutral society hinges on developing and deploying cutting-edge technologies across various sectors. These technologies reduce emissions, enhance EE, enable the integration of RE into the grid, and provide new solutions for hard-to-abate sectors.

Renewable energy technologies (RETs)

The growth of RE technologies has been a cornerstone of global decarbonization efforts. Solar photovoltaic (SPV) technology, for instance, has seen dramatic cost reductions over the past decade, with the levelized cost of electricity (LCOE) for utility-scale SPV declining by over 85 % between 2010 and 2020 [47]. This has been driven by advancements in PV cell efficiency, economies of scale in manufacturing, and competitive auctions that have spurred investment. Wind energy (WE) has also made significant strides, particularly in offshore wind, where capacity factors are higher, and the potential for large-scale deployment is substantial. Offshore wind projects in Europe, including the Hornsea One and Hornsea Two wind farms in the UK, demonstrate the viability of this technology in contributing to national carbon neutrality goals. The integration of floating wind turbines (WTs) is expanding the potential for offshore wind, particularly in deep-water regions where traditional fixed-bottom turbines are not feasible [48].

Energy storage (ES) solutions

ES is critical for addressing the intermittency of RESs like solar and wind. Lithium-ion batteries dominate the energy storage market, with prices falling by nearly 90 % over the past decade. This price drop has enabled the deployment of large-scale battery storage systems, such as the Hornsdale Power Reserve in South Australia, which helps stabilize the grid by providing rapid response power during fluctuations in energy supply and demand (ESD) [49]. Emerging storage technologies, including solid-state and flow batteries, offer the potential for even greater energy density, safety, and longevity [50]. Additionally, pumped hydro storage remains the most widely used form of large-scale energy storage, accounting for over 90 % of global storage capacity [51]. This technology is particularly effective in regions with suitable topography, such as mountainous areas.

Carbon capture and storage (CCS)

CCS is essential for achieving net-zero emissions, particularly in sectors with challenging decarbonization, including heavy industry and natural gas power generation. The Sleipner CCS project in Norway has been operational since 1996, capturing approximately 1 million tonnes of CO2 annually from natural gas processing and storing it beneath the North Sea [52]. The success of such projects demonstrates the viability of CCS as a critical component of the global decarbonization strategy. However, the deployment of CCS faces significant challenges, including high costs, the need for extensive infrastructure, and public acceptance. The development of carbon utilization technologies, which use captured CO_2 to produce valuable products, including synthetic fuels, chemicals, and building materials, offers a pathway to improving the economics of CCS.

Energy efficiency improvements

EE remains one of the most cost-effective methods for reducing emissions. Building insulation, lighting, and heating system improvements can significantly lower energy consumption. For example, the "Passive House standard," which originated in Germany, reduces building energy use by up to 90 % compared to conventional buildings, primarily through superior insulation and airtight construction [53]. In the industrial sector, process optimization [54] and the adoption of energy-efficient technologies (EETs), including variable frequency drives [58], waste heat recovery [59], and high-efficiency motors [60], can lead to substantial energy savings. The transport sector, which accounts for nearly a quarter of worldwide CO_2 emissions, is also seeing significant improvements in EE through the adoption of electric vehicles (EVs) and advancements in battery technology [55].

Behavioral changes and social engagement

While technological advancements are critical, behavioral changes and social engagement are equally important in the journey toward carbon neutrality. Public support for climate action and changes in consumption patterns and lifestyle choices can significantly accelerate the transition to a low-carbon society.

Public awareness and education

Educating the public about the benefits of clean energy and the importance of reducing carbon emissions is essential for building broad-based support for climate policies. Research indicates that campaigns emphasizing RES's individual and community advantages, including better air quality, job opportunities, and enhanced energy security, can significantly boost public support for RES initiatives [56–58].

Behavioral economics and incentives

Behavioral economics offers valuable insights into how individuals and communities can be encouraged to adopt low-carbon behaviors. Financial incentives, such as subsidies for energy-efficient appliances, tax credits for home retrofits, and rebates for electric vehicle purchases, have effectively driven consumer behavior towards more sustainable choices. The success of such programs can be seen in countries like Norway, where generous EV incentives have made electric cars more than 60 % of new car sales [59].

Community engagement and empowerment

Community-based RE projects empower local communities to participate actively in the energy transition. For example, community solar projects allow individuals and businesses to invest in shared SE installations and peer-to-peer community energy trading, providing them with clean energy and financial returns. These projects also foster a sense of ownership and engagement, which can lead to greater public acceptance of RE developments [60,61]. Moreover, involving communities in the planning and decision-making process for RE projects can reduce opposition and increase the likelihood of project success. Engaging with stakeholders early and transparently can help address concerns about land use, environmental impacts, and other potential issues.

Global equity considerations

Achieving carbon neutrality on a global scale requires addressing the disparities between developed and developing countries. Developing nations often face significant challenges, including limited access to technology, financial constraints, and a lack of infrastructure. International support in the form of climate finance, technology transfer, and capacity building is crucial for enabling these countries to pursue low-carbon development pathways. The Green Climate Fund (GCF) is one mechanism that aims to address these challenges by providing financial resources to developing countries for climate mitigation and adaptation projects. Since its inception, the GCF has approved over USD 10 billion in funding for projects that support RE, EE, and resilience-building efforts in vulnerable communities [62].

Beyond policy, technology, and behavioral change, clean energy serves as the cornerstone of achieving carbon neutrality. The following subsection discusses the critical role of renewable and low-carbon energy sources in reducing greenhouse gas emissions.

Clean energy as a cornerstone of carbon neutrality

Consistent with the methodology of this study, the following subsections synthesize evidence from existing literature and secondary data sources. Quantitative insights (such as carbon tax formulations and emission trends) are drawn from established studies to highlight the practical significance of clean energy pathways.

As the global community intensifies its efforts to combat CC, clean energy has become a cornerstone in pursuing carbon neutrality. Clean energy sources, which include solar, wind, hydropower, and geothermal, offer the dual benefits of reducing GHGEs and

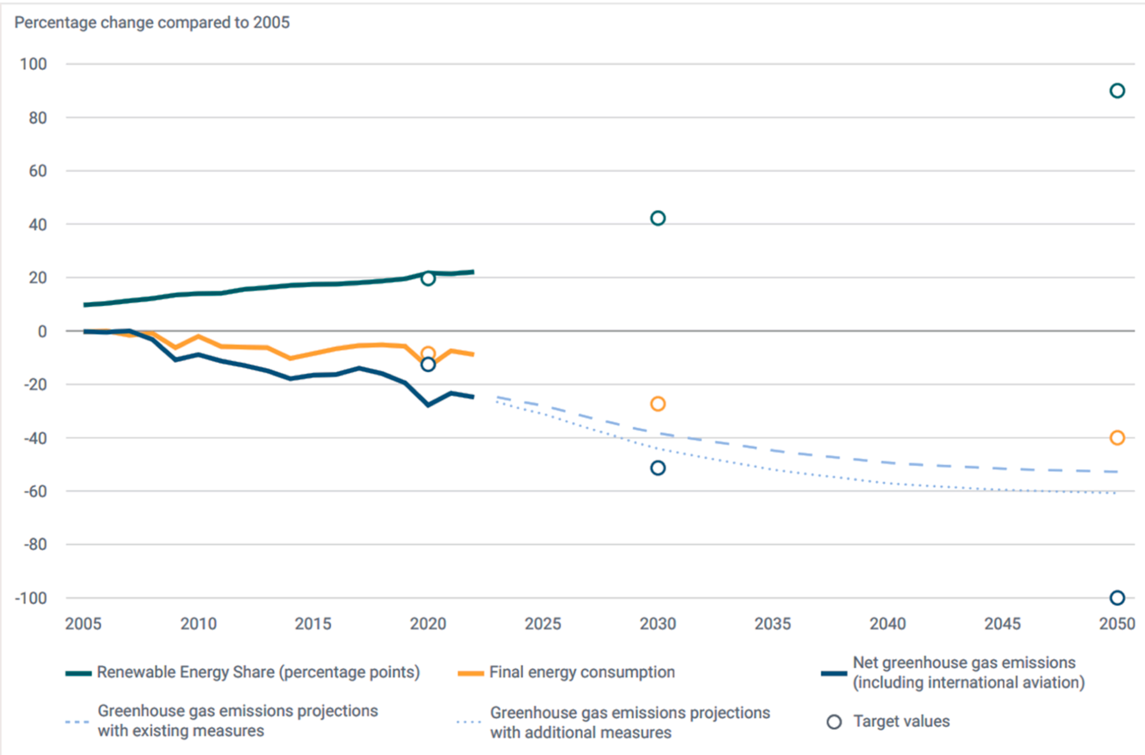

Fig. 2. EU achievement in 2020 and further progress towards 2030 and 2050 climate and energy targets.

promoting SD. Unlike traditional FFs, major contributors to global warming due to their high CO_2 emissions, clean energy technologies produce minimal to no direct emissions. This makes them indispensable in the global strategy to achieve CN by mid-century. The transition to clean energy is a technical challenge and a socio-economic imperative. The adoption of RETs is growing rapidly worldwide, driven by environmental concerns and economic opportunities. According to the International Renewable Energy Agency (IRENA), RE capacity has more than doubled over the past decade, and renewables now account for over a quarter of global electricity generation [63]. This shift is crucial for reducing the energy sector's carbon footprint, ensuring energy security, improving public health, and creating new economic opportunities in the green energy sector. However, integrating clean energy into the global energy mix could be more challenging. These include technical issues related to the intermittency of RESs, economic barriers, including high upfront costs, and the need for supportive policy frameworks. Despite these challenges, the global trend towards clean energy is irreversible, as evidenced by the growing investments in RE technologies [64] and the increasing number of countries committing to CN targets by 2050.

Role of clean energy in reducing GHGEs

Clean energy plays a critical role in mitigating the impacts of CC by reducing GHGEs. The transition to RESs like wind, solar, hydro, and nuclear energy is essential for achieving carbon neutrality and reducing the global carbon footprint. The adoption of RESs has shown a significant reduction in CO2 emissions, indicating that these sources effectively replace traditional FFs and contribute to carbon neutrality. Similarly, EE and RE are vital in reducing carbon emissions, especially in developing countries. The study highlights that energy efficiency consistently reduces CO2 emissions across different quantiles, with RE contributing significantly [65]. Material efficiency strategies such as efficiently using building materials, vehicles, and electronics can substantially reduce GHG emissions. Replacing traditional materials with more sustainable options, such as timber, and improving recycling efforts are also effective strategies [66]. On the other hand, implementing environmental taxes and promoting clean energy policies in the European Union (EU) have effectively reduced GHG emissions. These policies have led to significant decreases in carbon emissions, mainly through demand-side and supply-side interventions. Since 2005, greenhouse gas emissions have significantly declined, with the total net emissions, including those from international aviation, reducing by 31 % relative to 1990 levels, as shown in Fig. 2 [67]. Within the buildings sector, there was an estimated 9 % decrease in greenhouse gas emissions. Likewise, the industrial sector experienced a notable drop in emissions during 2022, largely due to reduced output in energy-intensive industries driven by higher energy costs. In contrast, emissions in the energy supply sector are projected to have increased by 3 %, influenced by rising natural gas prices that enhanced coal's competitiveness and unexpected challenges in nuclear and hydropower facilities throughout 2022, as shown in Fig. 3 [67–69].

Furthermore, distributed energy resources, including combined heat and power (CHP) systems, have been identified as effective in

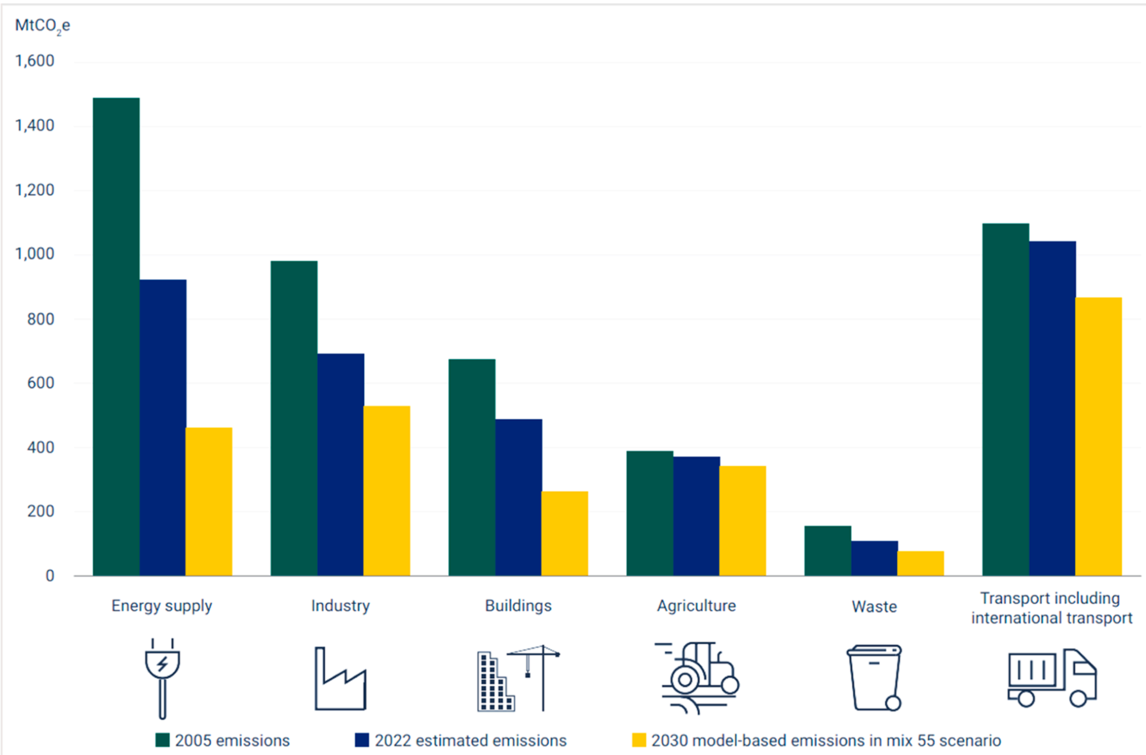

Fig. 3. EU Sectoral progress reduced and GHG emission trend towards 2030.

minimizing carbon emissions, particularly in the industrial and commercial sectors. However, their role diminishes as carbon reduction targets become more stringent, highlighting the need for a balanced approach to clean energy investments [70]. A mixed policy of coal capacity cut and carbon tax, with appropriate stringency levels, can also significantly improve energy conservation, carbon emission reduction, and economic growth [71]. To calculate the carbon tax, it is necessary to know how much carbon emissions are obtained from FF energy resources, shown in Eqs. 1 and 2. The carbon tax rate is considered an exogenous parameter. We assume that the carbon tax rate of each sector is identical and fixed.

$$CO_{2,n} = \sum_{m} E_{n,m} \cdot \alpha_m \tag{1}$$

$$CO_{2,m} = (H_m + G_m) \cdot \alpha_m \tag{2}$$

$$\mathrm{Ct}x_m = \gamma c \cdot \sum_{i} E_{n,m} \cdot \alpha_m \tag{3}$$

$$TCtx = \sum_{m} Ctx_m \tag{4}$$

where, $CO_{2,n}$ represents the carbon emission of the sector; the m denotes various kinds of fossil energy resource sectors, we assume they are heavy industry, building and construction, coal, petroleum, and gas industry. α_m is the carbon emission factor for fossil fuel energy resource energy, and is the consumption of fossil energy by households and governments$m$. The eq. 3 and eq. 4 express the carbon tax, where $\mathrm{Ct}x_m$denotes the carbon tax levied on fossil energy m, the total carbon tax $TCtx$ is shown in eq. 4, while the carbon tax rate is denoted with γc.

Solar and wind energy (SWE): high potential, low emissions

Solar and wind energy (SWE) generate electricity without direct GHG emissions and have become increasingly competitive with fossil fuels due to rapid cost declines. Their widespread adoption in countries such as Germany and China demonstrate their effectiveness: Germany's Energiewende has reduced energy sector CO_2 emissions by 40 % since 1990 [72], while China's large-scale SWE deployment supports its target to peak emissions by 2030 and achieve carbon neutrality by 2060 [73]. SWE are central to global decarbonization, with studies confirming their essential role in reducing carbon emissions [74]. In the European Union, solar and wind are projected to reach a 43 % share of renewable power generation by 2050, with wind offering the fastest expansion potential [75]. China's transition further highlights SWE as the backbone of a new power system, though it requires parallel investments in storage, flexibility, and policy support [76]–[78]. Comparative life-cycle analyses show wind energy to be the most efficient and sustainable among renewables, underscoring SWE's pivotal contribution to long-term carbon neutrality [77]. Still, challenges related to energy storage, system flexibility, and policy frameworks must be addressed to fully realize their potential in achieving carbon neutrality [78].

Hydropower and geothermal energy: reliable and sustainable

Hydropower, the largest renewable energy source globally, plays a vital role in reducing GHG emissions by replacing fossil fuel combustion. Despite environmental and social concerns, such as ecosystem disruption and displacement, its net CO_2 reduction benefits are substantial. Hydropower is widely recognized as a clean, low-carbon, and cost-efficient option, particularly when integrated with digitalized management systems that enhance sustainability and support the EU's carbon-neutral objectives [79]. Geothermal energy (GTE) also offers significant decarbonization potential by providing reliable, base-load electricity with minimal emissions. Iceland demonstrates its viability, meeting nearly all of its energy demand from renewable sources [80]. However, GTE faces barriers such as high capital costs, resource location, and public acceptance. Overcoming these requires policy support, technological innovation, and community engagement [81]. Hybrid systems that combine GTE with other renewables, such as biomass, further enhance system sustainability. For instance, Cornell University's integration of geothermal heating with biomass waste highlights both technical feasibility and the importance of supportive policies for economic viability [82].

Taken together, global experiences demonstrate that clean energy, combined with efficiency measures, is essential for reducing greenhouse gas emissions and supporting sustainable growth. Building on these lessons, the following section turns to Nigeria's specific pathway toward carbon neutrality, highlighting its energy landscape, policies, challenges, and opportunities.

Nigeria's pathway to carbon neutrality

Nigeria's journey towards carbon neutrality is both a challenge and an opportunity. As one of Africa's largest economies and a major oil producer, Nigeria faces the dual challenge of reducing its dependence on FFs while fulfilling the energy needs of a growing population. However, the country's abundant RESs, particularly in solar and hydropower, offer significant potential for clean energy development.

Overview of Nigeria's energy landscape (ELS)

Nigeria's energy sector is characterized by a heavy reliance on FFs, particularly oil and natural gas, which have been the backbone of the country's economy for decades. In Nigeria's primary energy supply, Biomass dominates the energy mix, with a share of 43 %, as per 2015 statistics [7]. The upper bound in current scenarios referred to as 2015 on RE resources, including small and large hydropower plants, wind and solar, and bio-energy, are depicted in Table 2. In tune with the deliverables of Nigeria's energy transition master plan, more industries are now deploying gas power generators and gas-fueled buses, which have proven to be more economical for their balance sheets than diesel and premium motor spirits [83,84]. However, as Africa's largest oil producer and the world's sixth-largest exporter of liquefied natural gas (LNG), Nigeria's economy is highly vulnerable to fluctuations in global oil prices [85]. This dependency poses financial risks and contributes significantly to the country's GHGEs (CO2 emissions from FFs and industry), making the transition to a low-carbon economy a complex challenge, as illustrated in Fig. 4 [86,87].

Despite these challenges, Nigeria has abundant RESs, including solar, hydro, wind, and biomass. SE, in particular, stands out because of Nigeria's geographic location, which provides an average SR of 5.58 kWh/m^2/day, making it one of the highest in Africa [88]. However, the exploitation of these resources has been limited by factors such as inadequate infrastructure, policy inconsistencies, and financing challenges.

National policies and strategic initiatives for Nigeria

Nigeria's dedication to achieving carbon neutrality is evident through various policy frameworks and strategic actions to advance RE and enhance EE. The government, in partnership with the United Nations Development Programme (UNDP), formulated the "Nigeria Renewable Energy Master Plan (REMP)," which provides a strategy to raise the share of RE in the national energy mix from 13 % in 2015 to 23 % by 2025 and 36 % by 2030. This plan prioritizes the growth of solar, small hydro, and biomass energy sources while promoting efficiency improvements across multiple sectors [89].

Alongside the REMP, Nigeria's Energy Transition Plan (NETP), introduced in 2022, forms a crucial part of the nation's roadmap to reaching net-zero emissions by 2060. The plan presents a detailed strategy for reducing emissions in the energy sector, increasing access to sustainable energy, reducing reliance on FFs, and fostering investment in low-carbon innovations. The NETP establishes a timeline and structured framework for achieving emission reductions across five key sectors [90]. The residential sector accounts for nearly half of the nation's gross final energy consumption, making it the largest contributor [91,92], as illustrated in Table 3. Within the ETP scope, approximately 65 % of Nigeria's emissions are affected, as depicted in Fig. 5 [93]. Nigeria's path to net-zero emissions is expected to result in significant net job growth, generating up to 340,000 jobs by 2030 and 840,000 by 2060, primarily driven by major sectors, as depicted in Fig. 6 [93]. The strategy also underscores the significance of global assistance, including climate finance and technology transfer, to achieve these ambitious goals.

Moreover, Nigeria's participation in global climate initiatives, including the African RE Initiative (AREI) and the Climate Change Act of 2021, which established a framework for climate governance and accountability, further demonstrates the country's commitment to tackling CC and transitioning to a low-carbon economy [94].

Challenges to achieving carbon neutrality in Nigeria

Nigeria faces multiple challenges in its transition to carbon neutrality. Despite the target of achieving a 23 % renewable electricity share by 2025, progress in scaling RE capacity remains slow, with national electricity consumption estimated at 31.57 billion kWh annually [95]. The agricultural sector, though traditionally energy-light due to low mechanization, is beginning to shift through initiatives from the Bank of Agriculture and efforts to strengthen the value chain for competitiveness [96,97]. Oil holds a comparable share of Nigeria's primary energy needs as bioenergy, yet the nation's four government-owned refineries remain non-functional, leading to heavy reliance on imports. While private and modular refineries are emerging, existing capacity is still inadequate to meet demand [98,99].

Several studies further illustrate systemic barriers. A LEAP-based analysis of low-carbon transport scenarios projected GHG emissions at 39 $MtCO_2eq$ by 2040 under business-as-usual, but noted potential reductions of 33 % (CM1) and 42 % (CM2) with countermeasures [100]. Another study identified gaps in Nigeria's NDC, including limited scope, over-reliance on solar PV, and neglect of advanced emission-control technologies, recommending more transparent and ambitious processes [101]. Using the MESSAGE model, another analysis showed that natural gas and oil plants dominate Nigeria's power mix; however, with CO_2 restrictions, nuclear power plants emerge as the most viable alternative [102].

Economic dependence on fossil fuels

One of Nigeria's most significant challenges to carbon neutrality is its heavy reliance on oil and gas revenues. The oil sector

Table 2
Upper bound on RESs in current scenarios.

Energy Source	2015	Total	Consumed in 2015 (%)
Large Hydro Power	1.9 GW	24 GW	8 %
Small Hydro Power	0.06 GW	3.5 GW	8 %
Wind Power	0 GW	3.2 GW	0 %
Solar PV	0.017 GW	210 GW	0 %
Concentrated Solar PV	0 GW	88.7 GW	0 %
Bio-energy	1229 PJ	29,800 PJ	4 %

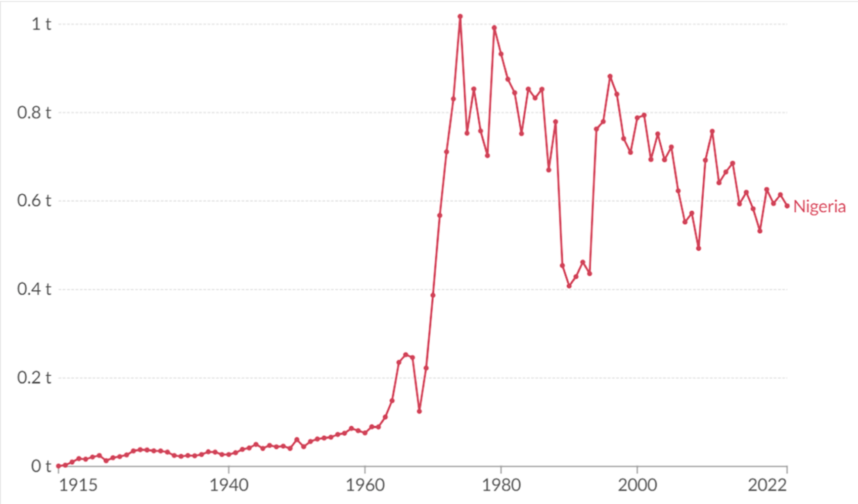

Fig. 4. Nigeria Per capita CO2 emissions from 1915–2022 [87].

Table 3
Renewable energy distribution in different sectors based on current and future scenarios.

Energy Sector	2020	2030	2040	2050
Residential	721 PJ	826 PJ	1018 PJ	949 PJ
Transport	0 PJ	18 PJ	123 PJ	277 PJ
Industry	239 PJ	580 PJ	1208 PJ	2417 PJ
Commercial	102 PJ	210 PJ	354 PJ	480 PJ
Agriculture	0 PJ	0 PJ	1 PJ	2 PJ

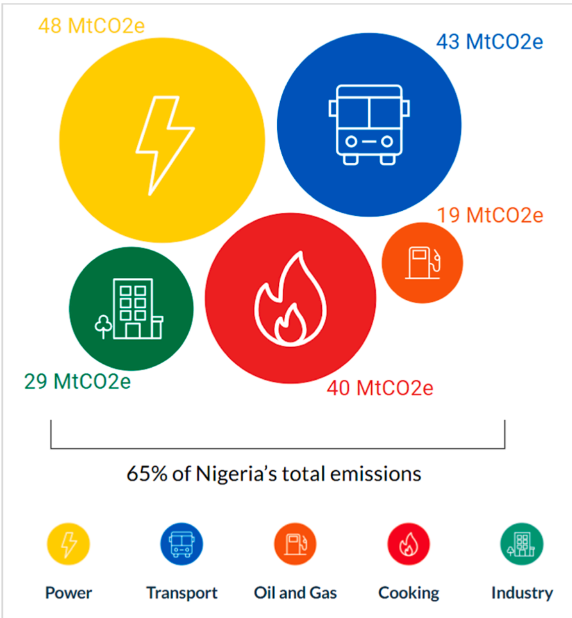

Fig. 5. Nigeria's sector-wise net-zero total emissions.

accounts for a substantial portion of Nigeria's GDP, government revenues, and foreign exchange earnings. This dependence creates a complex dilemma: transitioning from fossil fuels could undermine economic stability, yet continuing reliance on these fuels exacerbates environmental degradation and climate vulnerability. The challenge is further compounded by the need for substantial

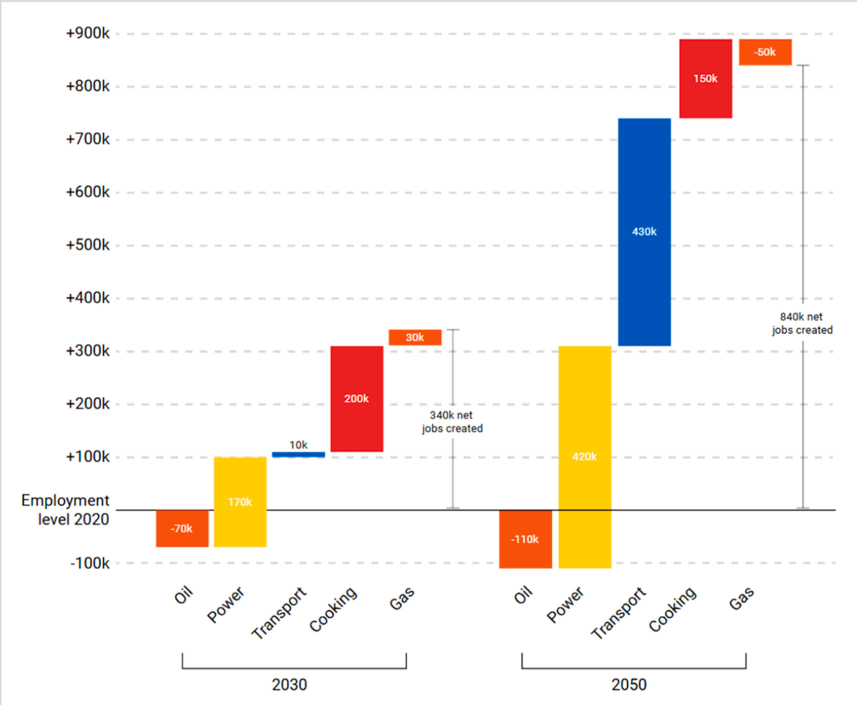

Fig. 6. Net job creation per sector in Nigeria as per ETP.

investments in RE infrastructure, which requires domestic funding and international financial support [103].

Energy access and infrastructure deficits

Nigeria's energy sector is plagued by significant infrastructure deficits, particularly in electricity generation and distribution. The national grid is unreliable and has limited reach, with many rural areas lacking access to electricity altogether. Approximately 85 million Nigerians, about 43 % of the population, live without access to grid power. Expanding RE through decentralized solutions like solar mini-grids is crucial for improving energy access and supporting economic development in these underserved areas [104].

Policy implementation and governance

While Nigeria has made strides in developing policy frameworks for RE and climate action, implementing these policies remains a major challenge. Regulatory uncertainties, inconsistent policy enforcement, and bureaucratic inefficiencies hinder the effective execution of RE projects. Additionally, governance challenges, including corruption and political instability, further complicate the landscape for energy transition efforts [105].

Financing and investment barriers

Financing remains a critical barrier to the large-scale deployment of RE in Nigeria. The high upfront costs associated with RE projects and perceived risks limit public and private investment availability. International climate finance is essential to bridge this gap, but accessing these funds requires robust project proposals, solid institutional frameworks, and transparent governance structures [106].

Opportunities for renewable energy development in Nigeria

A bottom-up analysis indicates that Nigeria could attain a fully RE supply by 2050 through the deployment of utility-scale solar photovoltaic systems and onshore wind turbines. Carbon dioxide emissions are projected to reach their highest point by 2030 before dropping to zero by 2050. Shifting to 100 % renewable electricity is more cost-effective and has the potential to generate 1.54 million jobs for Nigerians by 2050, compared to traditional approaches [107].

Solar power

Solar energy represents the most significant opportunity for Nigeria to diversify its energy mix and reduce carbon emissions. The country's vast solar potential, particularly in the northern regions, makes it an ideal candidate for large-scale solar power development. Recent projects, such as the Kano Solar Power Project, aim to harness this potential by generating up to 100 MW of electricity. This initiative forms a component of the larger Nigeria Electrification Project (NEP), backed by the World Bank, aiming to deliver dependable and sustainable electricity to underserved and rural areas using solar mini-grids and standalone solar solutions [108]. Solar home systems and mini-grids are progressively recognized as effective means to power remote regions without access to the national grid. These decentralized energy options help lower emissions and enhance the lives of millions of Nigerians by offering dependable electricity to homes, schools, and small enterprises.

Hydropower

Hydropower is another key RES with significant untapped potential in Nigeria. The country's river systems, particularly the Niger and Benue Rivers, offer substantial opportunities for both large-scale and small-scale hydropower development. The Mambilla Hydropower Project, currently under construction, is expected to be one of the largest in Africa, with a capacity of 3050 MW. Once completed, this project will significantly boost Nigeria's electricity generation capacity and minimize its reliance on FFs [109].

Wind and biomass

While solar and hydropower are the primary focus, Nigeria has the potential for wind and biomass energy. The wind potential is particularly promising in coastal areas and the northern regions. Small-scale wind turbines could provide an additional source of power for rural electrification. Biomass, derived from agricultural residues, forestry waste, and other organic materials, offers another avenue for RE, particularly in rural areas with abundant resources. Biomass energy could also support the agricultural sector by providing farmers with an additional income stream by selling agricultural residues for energy production [110].

Case studies and success stories of Nigeria

Kano solar power project

The Kano Solar Power Project is a flagship initiative in Nigeria's RE sector, designed to generate 100 MW of electricity using solar PV technology. Located in Kano State, this project is expected to power over 1 million homes and significantly reduce the state's carbon footprint. The project is part of a broader effort to harness Nigeria's solar potential, particularly in the northern regions where solar radiation levels are highest. The success of this project could serve as a model for similar initiatives across the country, demonstrating the viability of large-scale solar power in Nigeria [108].

Mambilla hydropower project

The Mambilla Hydropower Project, once completed, will be one of the largest hydropower plants in Africa, with a capacity of 3050 MW. Located in Taraba State, the project is designed to harness the power of the Donga River and will contribute significantly to Nigeria's electricity generation capacity. The project is expected to provide electricity to millions of Nigerians, reducing the country's dependence on FFs and contributing to its carbon neutrality goals [109]. However, the project has faced significant challenges, including delays related to financing, environmental concerns, and land acquisition issues. Despite these hurdles, the Nigerian government, in collaboration with international partners, has remained committed to the project, recognizing its potential to transform the country's energy landscape. The successful completion of the Mambilla Hydropower Project would enhance energy security and demonstrate Nigeria's capacity to undertake large-scale RE projects that can significantly reduce GHGEs [111].

Solar home systems (SHS) and mini-grids (MGs)

In addition to large-scale projects like the Kano Solar Power Project, Nigeria has seen significant progress in deploying SHS and MGs, particularly in rural areas. These decentralized energy solutions are part of the Nigeria Electrification Project (NEP), which aims to provide electric power to communities not linked to the national electric power network. By using solar PV technology, SHS and mini-grids offer a clean, reliable, and affordable source of energy, thereby reducing the reliance on diesel generators, which are both costly and environmentally harmful [112]. One notable success story is the deployment of solar MGs (SMGs) in rural villages across the states of Ogun, Niger, and Sokoto. These MGs have provided electricity to thousands of households, enabled small businesses' growth, improved healthcare services, and enhanced educational opportunities. The NEP's approach of integrating public-private partnerships has been crucial to its success, attracting investment from local and international companies and ensuring the sustainability of these projects [113].

Cross-Border renewable energy collaboration

Nigeria is also exploring opportunities for cross-border RE projects as part of the West African (WA) Power Pool (WAPP) initiative. WAPP aims to create a regional electric power market in WA, allowing member countries, including Nigeria, to share and trade electricity generated from RESs. This collaboration is essential for stabilizing the electricity supply in the region, where many countries face similar challenges related to energy access and grid reliability [114]. One of the key projects under WAPP is the construction of the North Core Transmission Line, which will connect Nigeria with Niger, Burkina Faso, and Benin. This transmission line will enable the export of excess electric power from Nigeria's RE projects, such as hydropower and solar, to neighboring countries. The successful implementation of this project would not only strengthen regional energy security but contribute to Nigeria's goal of becoming a regional leader in clean energy [115].

Potential impacts of Nigeria's transition to carbon neutrality

Economic transformation

Nigeria's transition to a carbon-neutral economy has the potential to transform its economic landscape. Nigeria can diversify its economy by minimizing its dependence on oil and gas and creating new growth opportunities in RE, EE, and green technology. The RE sector alone is expected to generate thousands of new jobs, from manufacturing and installation to maintenance and operations. Additionally, investments in EE can lead to significant cost savings for businesses and consumers, improving competitiveness and economic resilience. Moreover, shifting to a low-carbon economy could enhance Nigeria's position in international markets, particularly as global demand for carbon-intensive goods declines and consumers increasingly favor products and services with a lower carbon footprint. By positioning itself as a leader in RE in Africa, Nigeria could attract foreign investment and become a hub for green technology innovation and manufacturing [116].

Environmental and health benefits

The environmental benefits of Nigeria's transition to CN are substantial. Reducing GHGEs will contribute to global efforts to mitigate climate change, helping to prevent the severe impacts of rising temperatures, such as extreme weather events, sea-level rise, and loss of biodiversity. In addition, adopting clean energy technologies will significantly reduce air pollution, a major public health concern in Nigeria. Cleaner air will improve health outcomes, particularly in urban areas with poor air quality due to the widespread

Table 4
Existing study on the EECN and Climate Change Mitigation.

Study Focus	Key Points	Challenges	Recommendations	Ref.
Vacuum Insulation Glazing (VIG)	Superior insulation technology with thermal transmittance around 0.5 W/m^2·K	High costs compared to standard IGUs and triple-glazed windows	Optimize manufacturing processes and integrate VIG with intelligent technologies	[120]
COVID-19 Impact on Carbon Emissions	Significant reduction in carbon emissions during the pandemic	Varying clean EE across countries	Enhance free trade and corporate environment for energy performance	[122]
Smart Cities	Use of advanced technology and data analytics to mitigate climate change	High industrial sector emissions driven by fossil fuels	Encourage eco-friendly practices and global collaboration	[123]
AI in Energy Efficiency	AI optimizes energy systems and enhances decision-making	Challenges in implementing AI-based approaches	Leverage AI to achieve CC mitigation goals	[124]
Energy Efficiency in Balkan Countries	Energy efficiency and pollution are obstacles to carbon neutrality	Economic development is not strongly linked to EE	Qualitative data for a better understanding of carbon-neutral future	[125]
Energy Efficiency Labeling (EEE)	EEE programs reduce CO2 emissions significantly	Need for widespread adoption and public policies	Apply EEE to household appliances and incentivize non-polluting vehicles	[126]
Energy Efficiency in OECD Countries	Focus on GDP growth over emissions reduction	Weak focus on sustainable economic growth	Balance economic growth with emission reduction efforts	[127]
Energy Efficiency in Various Sectors	Reduces energy consumption and increases comfort	Need for retrofitting buildings with energy-efficient features	Combine energy efficiency with other solutions to combat climate change	[128]
Pulp and Paper Sector in Canada	Significant potential for emissions reduction through EE.	High initial costs and adoption challenges	Adopt efficiency measures to improve competitiveness	[129]
Energy Efficiency in G7 Countries	Long-term relationship between EE and emissions	Positive correlation between RE and emissions	Further discussion is needed to understand this relationship	[130]
Achieving Carbon Neutrality by 2050	Importance of renewable energy and BEV expansion	Challenges in improving the thermal efficiency of engines	Focus on lean burn technology and carbon-neutral fuels	[131]
Energy Efficiency in China	Mixed relationship between economic growth and emissions	Challenges in policy implementation	Revise energy efficiency policies for better environmental recovery	[132]
Climate Change Mitigation Technologies	The negative effect of CMTs on CO2 emissions	Natural resources rent increases emissions	Increase energy productivity and adoption of clean technology	[133]
Industrial Sector Decarbonization	Critical for achieving climate change goals	Short/medium-term strategies insufficient alone	Implement a sector-specific approach to achieve net-zero emissions	[134]
Energy Efficiency in the U.S.	Focus on low-cost, immediate routes to decarbonization	Unclear role in achieving net-zero emissions	Review energy efficiency pathways for industrial decarbonization	[135]
Energy Efficiency in OECD Countries (Ecological Footprint)	Positive impact of energy EE and RE on environmental quality	GDP contributes to environmental degradation	Transition to renewables enabled by EE and technology	[136]
Technology and Renewable Energy	Effective in curbing GHGEs	Interaction between technology and the manufacturing sector	Support the EKC hypothesis and provide policy directions for carbon neutrality	[137]
Green Economic Growth (GEG)	Positive predictors include energy efficiency and technology	Importance of government integrity	Develop energy policies to mitigate environmental degradation	[138]
Carbon-Neutral Building Designs	Superior energy efficiency through design	The construction stage uses the least technical energy	Systematic design method using big data and innovative theories	[139]
National GHG Inventories	Policies favor biomass over energy-efficiency technologies	Opposition to high-efficiency CHP production	Expand the study to include other policy and geographical areas	[121]
Carbon Neutrality in India	Energy intensity and green technology de-escalate emissions	Population challenge	Appropriate orientations and low-carbon energy profiles	[140]
Resource Efficiency and Globalization	Coal efficiency and natural gas efficiency reduce CO2 emissions	Globalization and economic growth intensify emissions	Address globalization factors to reduce emissions	[141]

use of diesel generators and industrial emissions [117].

Social and community impacts

The social effects of Nigeria's energy transition are also crucial. Increasing access to clean, reliable, and affordable electricity will bring widespread advantages to Nigerian communities, especially in rural areas. Better energy access will boost educational opportunities, foster the development of small and medium-sized enterprises (SMEs), and enhance the provision of vital services such as healthcare and sanitation [118]. The emphasis on decentralized RE solutions, like solar mini-grids, will enable villages to manage their electricity needs and support local economic growth [119]. Additionally, the shift to a carbon-neutral economy offers a chance to tackle energy poverty and inequality in Nigeria. By focusing on RE infrastructure investments and guaranteeing affordable electricity for all Nigerians, the government can help close the energy access divide and foster inclusive growth.

Energy efficiency and carbon neutrality: global insights and Nigeria's integration

Global role of energy efficiency in carbon neutrality

Energy efficiency (EE) is a cornerstone of global carbon neutrality strategies, with technological advances such as vacuum insulation glazing (VIG) reducing CO_2 emissions in energy-intensive sectors like coal and natural gas [120]. Investments in energy-efficient technologies (EETs) lower consumption and accelerate low-carbon transitions, particularly in high-demand sectors such as

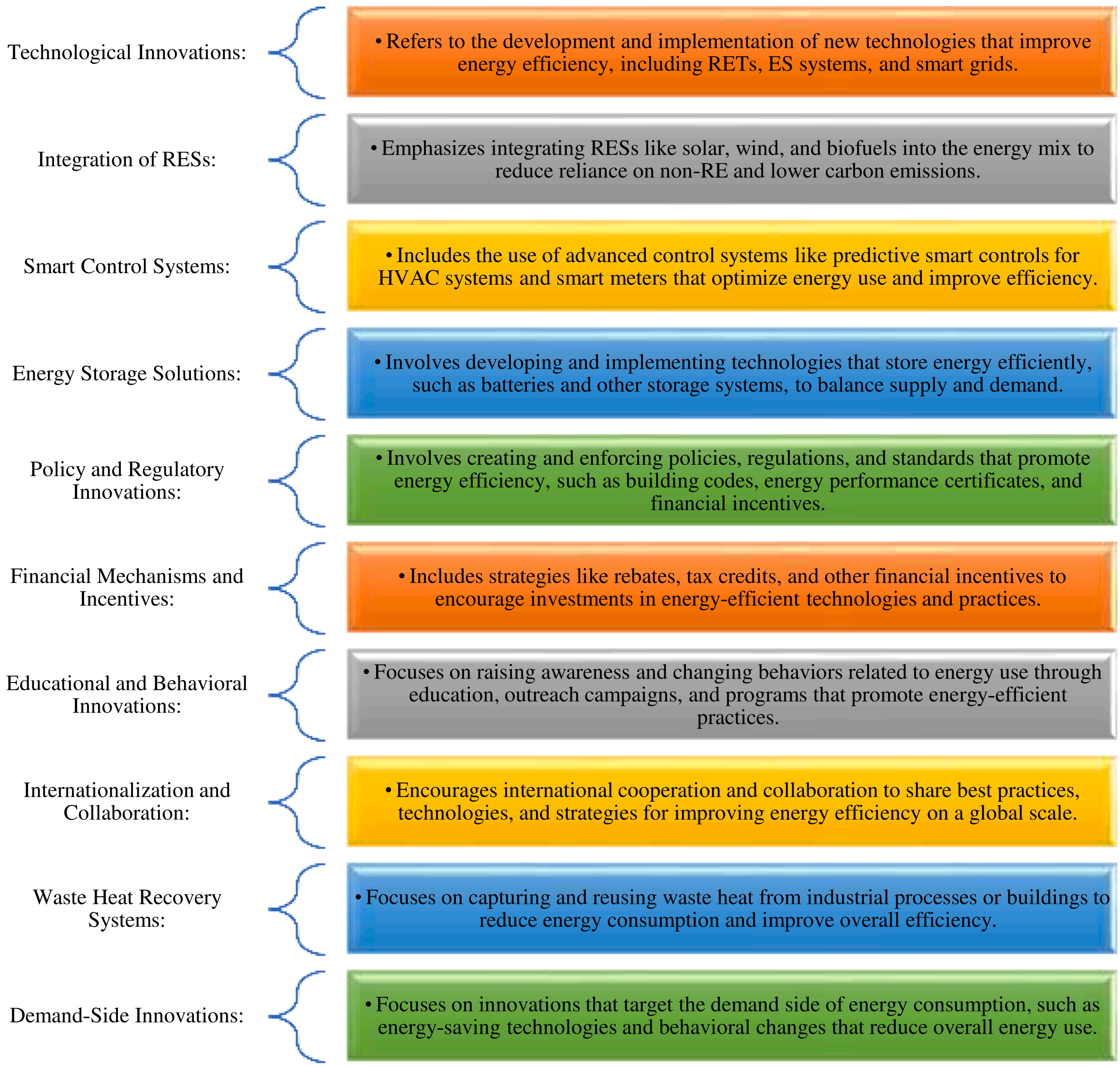

Fig. 7. The innovative approaches for improving EE, reducing energy consumption, and promoting sustainability across various sectors.

Table 5
Existing study on types of innovative approaches for energy efficiency.

Ref.	Objectives	Types of Innovative Approach	Examples of Approaches	Lessons from the Study
[124]	Reduce energy consumption while maintaining the same level of service or output.	• Technological	Improvements in heating, cooling, appliance efficiency, energy-saving measures in manufacturing	Programs reduce GHGEs, contribute to net-zero goals, and are cost-effective.
[125]	Promote EE using advanced technologies and behavioral changes.	• Technological • Integration of RES • Behavioural	Smart meters, energy management systems (EMSs), automation, and public awareness campaigns	These approaches result in cost savings and reduced reliance on fossil fuels.
[126]	Enhance low-carbon technology innovation efficiency in new energy enterprises.	• Technological • Integration of RES • Incentives and Support • Collaboration	Smart meters, energy management systems, energy-efficient appliances	Importance of technology integration and government support in EE.
[127]	Promote sustainable energy practices through technology integration.	• Technological • Integration of RES • Sustainability Focus • Behavioural Change • Financial Incentives • Collaboration	Smart grids, energy management systems, tax credits	Programs drive energy transformation and sustainability goals.
[129]	Promote green energy utilization and technological innovation in Bangladesh.	• Technological • Policy Framework	RESs, policy support for green energy	Programs are crucial for fostering a low-carbon economy in vulnerable regions.
[130]	Enhance EE in various sectors.	• Technological • Financial Incentives • Education and Training, • Collaboration	Smart meters, advanced building materials, energy management systems	Programs are essential for sustainability and EE improvement.
[133]	Enhance EE through advanced technologies and collaboration.	• Technological • Knowledge Spill over • Collaboration • Policy Support	Smart grids, RESs, tax credits	Collaboration and policy support are crucial for EE.
[134]	Promote EE to support carbon neutrality by 2050.	• Technology Adoption • Behavioural Changes	Smart meters, energy-efficient appliances	Widespread adoption of efficient technologies is crucial for carbon neutrality.
[138]	Enhance urban green economy efficiency through RE technology innovation (RETI).	• RES integration • Technological • Policy Support	Solar, wind, cleaner production methods	RETI promotes sustainability and EE in urban economies.
[141]	Enhance EE across various sectors, particularly in electricity generation and consumption.	• Technological • RES Integration, • Energy Storage Solutions • Smart Controls, • Policy and Strategy Development	Electric Heat Pumps, Predictive Smart Controls for HVAC, Expansion of RE, Development of Electricity Storage Technologies	Achieving EE requires a combination of technological innovation and strategic policy development. With advancements in materials, devices, and system architectures, a tenfold improvement in computing EE is possible by 2025.
[142]	Enhance EE through new technologies, practices, and policies, particularly in China's energy sector.	• Government Support, • Technological • Internationalization • Financial Mechanisms	Ultra-High Voltage (UHV) Power Transmission, Wind Energy, Solar PV, Nuclear Power	Government support and financial mechanisms are crucial for developing innovative EE technologies. Local government initiatives play a key role in fostering energy-efficient innovations.
[145]	Improve EE in buildings through regulatory policies and technological innovations.	• Regulatory Policies • Financing Mechanisms • Technological Innovations • International Efforts	Japan's Top Runner Program, Low-emissivity windows, Solid-state lighting	Stronger enforcement of appliance standards and building codes can significantly improve EE. Financing mechanisms that tie repayments to utility bills can make EE investments more attractive.
[146]	Promote energy savings and reduce carbon footprints through comprehensive approaches integrating technology, policy, and societal engagement.	• Demand-Side Innovations • Integration of Multiple Innovations • Supportive Policies and Legitimacy	Technological advancements, Behavioral changes, Policy measures	A comprehensive approach that integrates technology, policy, and societal engagement is crucial for overcoming barriers to the diffusion of low-carbon innovations. Ongoing research is necessary to enhance program effectiveness.
[147]	Reduce energy consumption and GHGEs while promoting sustainable practices through various programs.	• Incentive Programs, Education and Outreach, Research and Development	Financial incentives like rebates or tax credits, educational campaigns, Funding research for new technologies	Effective EE programs are integrated into broader energy policies and regularly evaluated for continuous improvement. These programs stimulate innovation and adoption of EETs.

manufacturing. EE is also central to international climate frameworks: the Paris Agreement anticipates that efficiency measures will deliver over 40 % of required GHG abatement by 2040 [2], while the EU's "energy efficiency first" principle prioritizes efficiency in energy policy [121]. Despite challenges such as fossil fuel dependence and high initial costs, the growing demand for renewables and efficient solutions presents opportunities for innovation and investment. Comprehensive strategies combining policy reform, circular economy principles, and social safeguards are essential for maximizing EE's role in climate change mitigation [56]. Table 4 summarizes EE contributions to carbon neutrality (EECN).

Innovations in energy efficiency

Recent innovations in energy efficiency (EE) are central to advancing a low-carbon economy by reducing energy demand across sectors while lowering both operational costs and environmental impacts (Fig. 7). The transition to clean and low-carbon energy systems highlights the importance of renewable energy sources (RESs), intelligent control systems, and energy storage (ES) solutions in optimizing energy use and reducing carbon emissions [142]. The effectiveness of low-carbon technology innovation (L-CTI) is shaped by government support, collaboration among enterprises and research institutions, and strong policy frameworks that foster sustainable development [143]. Emerging approaches, such as integrating IoT technologies for real-time emissions monitoring and adopting waste heat recovery systems, further enhance efficiency and sustainability [144]. In parallel, financial mechanisms (e.g., rebates, tax credits) and educational initiatives play an enabling role in encouraging investments in energy-efficient technologies (EETs), while international collaboration accelerates the exchange of best practices and global adoption of EE strategies [145]. Collectively, these innovations and policies form a comprehensive approach to energy management, supporting sustainable urban transitions and industrial rationalization, and ultimately driving the global shift toward a low-carbon future. Various researchers have studied innovative EE approaches, briefly summarized in Table 5. This table is organized into types of innovation, examples, and lessons learned from the studies.

Case studies: successful implementation of energy efficiency for carbon reduction

Implementing EE measures across various sectors plays a vital role in minimizing carbon emissions and mitigating CC. This section highlights critical case studies demonstrating how targeted energy management strategies, technological innovations, and policy interventions have reduced carbon footprints. For instance, educational institutions have achieved notable success by integrating EETs, such as replacing traditional lighting with LEDs and upgrading to high-efficiency air conditioning systems. These measures resulted in substantial energy savings and a marked decrease in carbon emissions, illustrating the effectiveness of systematic energy management in the education sector [146]. Energy efficiency remains a critical lever for carbon reduction in the industrial sector, especially in energy-intensive industries like iron and steel, pulp and paper, and cement. Adopting intelligent manufacturing practices, CHP systems, and ISO 50,001-based energy management systems (EMSs) have been shown to deliver immediate and long-term reductions in energy use and emissions. For example, a review of energy efficiency pathways across six industries emphasized the potential for strategic energy management to drive decarbonization by 2050, with ISO 50,001 implementations yielding higher annual energy performance improvements than traditional methods [135,147]. Similarly, the pharmaceutical industry has made significant

Table 6
Successful implementation of energy efficiency for carbon reduction in Nigeria.

Sector	Key Points	Challenges	Investment Needs	Lessons Learned	Ref
Construction	Advanced EETs have reduced energy consumption and operational costs.	Need for more education on social benefits.	Significant investment is needed.	Alignment with global sustainability goals.	[150]
Oil and Gas	Improved EE practices reduce greenhouse gas emissions and costs.	Integration of management and technological advancements.	Financial and policy support.	Essential for climate change mitigation.	[151]
Financial Development	Promotes short-term EE but challenges long-term due to debt constraints.	Managing debt to sustain long-term efficiency.	Sustainable financial development models.	Financial health influences EE outcomes.	[152]
Building Sector	Transition to low-carbon or zero-energy structures is crucial.	Significant public and private investment.	Collaborative efforts across stakeholders.	Enhances sustainability in urban development.	[153,154]
Transportation	Solar energy systems could reduce carbon emissions at refueling stations.	High initial investment in solar systems.	Feasibility studies for solar adoption.	Solar energy as a viable alternative to diesel.	[155]
Food and Beverage Industry	Retrofitting reduces energy consumption and CO_2 emissions.	Identification of inefficient equipment.	Investment in EET.	DSM techniques can significantly lower carbon emissions.	[156]
Residential Buildings	Prepaid meters and efficient appliances can drive energy-saving behaviors.	Market penetration of energy-efficient devices.	Subsidies for energy-efficient appliances.	Systematic approach needed for policy implementation.	[157]
Lighting Efficiency	Significant reduction in CO_2 emissions by adopting energy-saving lighting.	Adoption of efficient practices by individuals.	Policy support for energy-saving initiatives.	Simple measures can lead to substantial savings.	[158]

strides in aligning its operational strategies with sustainability goals, as demonstrated by a case study at a leading pharmaceutical R&D facility that achieved notable reductions in energy consumption and carbon footprint through comprehensive energy assessments and targeted interventions [148]. The review also underscores the importance of continuous improvement programs in energy-intensive industries, such as the refining and petrochemical sectors. A notable example is the Steam System Optimization Program (SSOP) implemented across 220 Japanese plants, which achieved a remarkable annual reduction of 562,000 tons of CO2 emissions while generating substantial financial savings [149]. The successful implementation of EE measures across various sectors in Nigeria has demonstrated the potential for substantial carbon footprint reductions, energy savings, and alignment with global sustainability goals, as shown in Table 6.

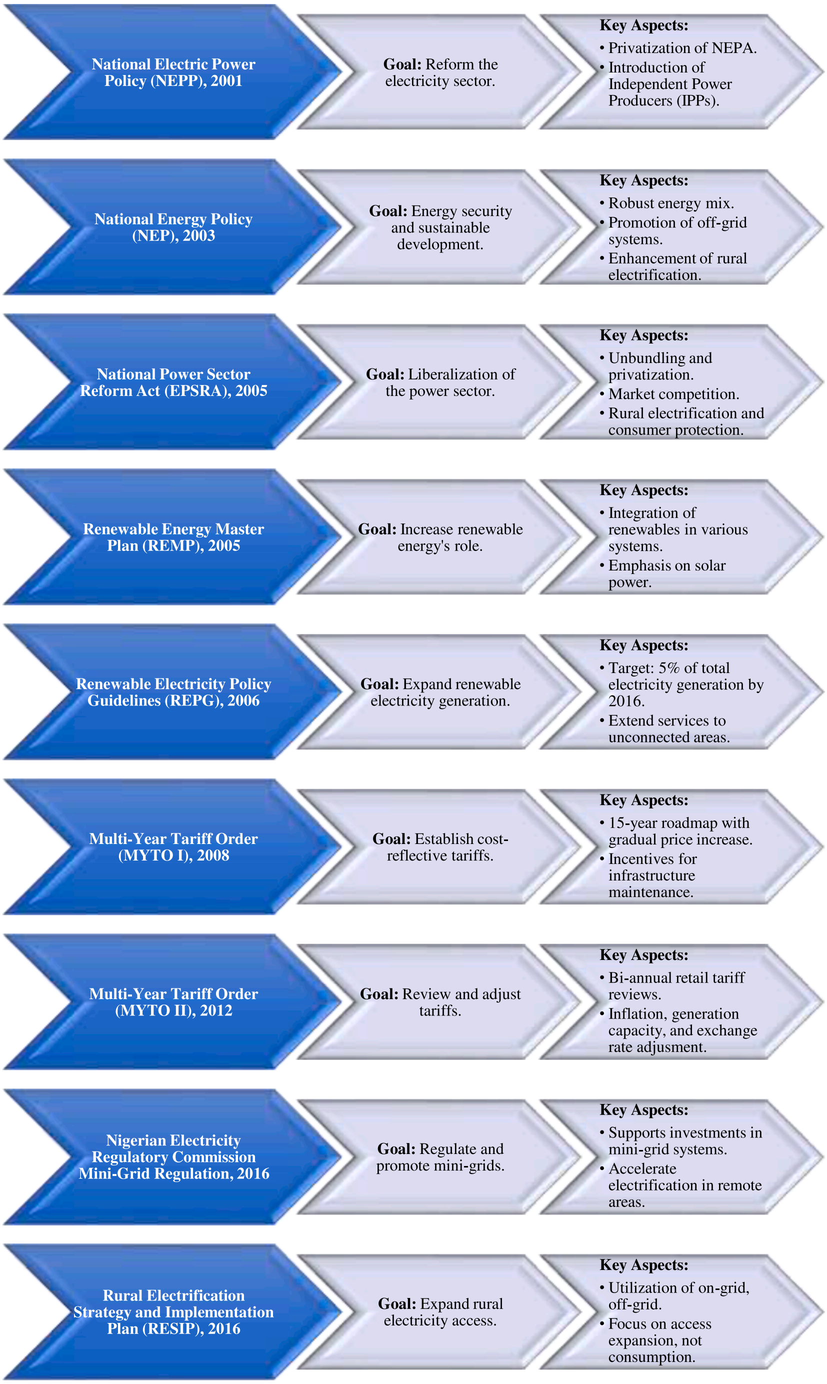

Fig. 8. Nigeria Electricity policies [167].

Energy efficiency in Nigeria: opportunities and challenges

Nigeria is currently experiencing a severe energy crisis, with approximately 90 million people lacking access to electricity, representing 12.5 % of the global population without power [159,160]. This challenge significantly undermines progress toward Sustainable Development Goal (SDG) 7, which emphasizes universal access to affordable, reliable, sustainable, and modern energy. The crisis is primarily attributed to insufficient power generation, weak transmission networks, and limited investment in energy infrastructure. Addressing these gaps requires a comprehensive strategy that prioritizes both energy efficiency (EE) and the integration of renewable energy sources (RESs) into the national grid. EE offers substantial opportunities to improve energy access, reduce costs, and enhance energy security. For instance, adopting energy management systems (EMSs) in industrial and commercial sectors can optimize energy use and yield financial savings. Residential sector studies in Nigeria reveal that retrofitting with energy-efficient technologies (EETs), such as upgraded lighting systems, can save up to 230 kWh annually with a payback period of nine months and a return on investment (ROI) of 126 %, while solar panels with batteries can generate annual savings of 3 MWh with an ROI of 26 % [159,160]. Similarly, in the oil and gas sector, which contributes heavily to emissions, EE improvements have the potential to reduce production costs and carbon footprints significantly [151]. Nonetheless, financial constraints, including limited access to long-term credit and the burden of national debt, pose major barriers to scaling EE investments, as highlighted in studies emphasizing the need for sustainable financing mechanisms [152]. Policy and regulatory shortcomings further constrain sectoral reforms, as Nigeria's power sector remains plagued by weak policies, inadequate infrastructure, and limited investor confidence [161]. Although government initiatives have

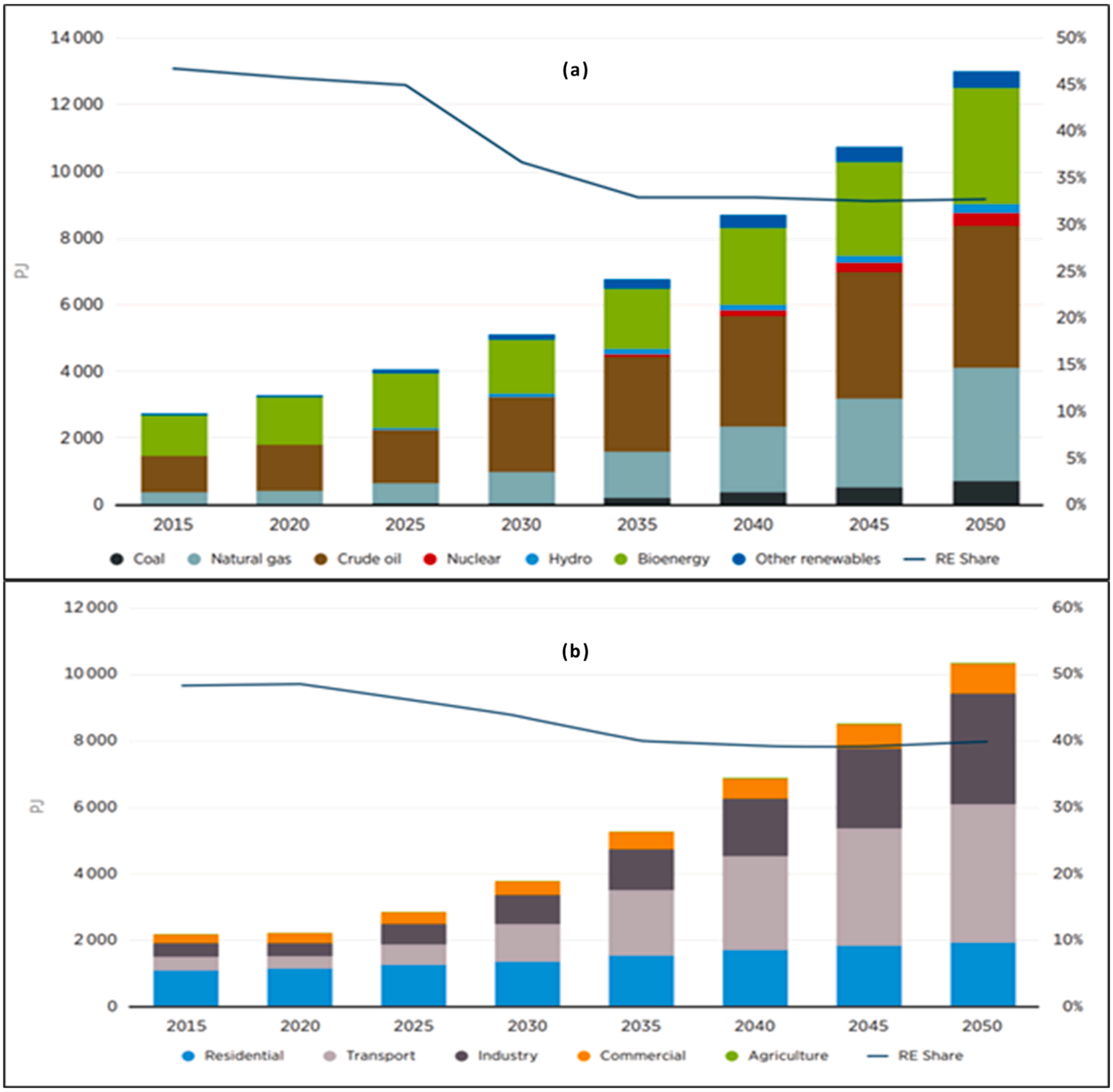

Fig. 9. (a) Nigeria's Primary Energy demand in future scenarios (PJ); (b) Final Nigerian Total Energy consumption in future scenarios (PJ).

been introduced to promote private sector involvement, diversify energy sources, and advance EE, their long-term effectiveness hinges on robust evaluation and policy enhancement.

Renewable energy represents a critical pathway for addressing Nigeria's energy crisis and achieving sustainable development. Despite its heavy reliance on fossil fuels, the country is endowed with vast renewable resources, including solar, wind, hydro, and biomass, which remain underutilized due to regulatory bottlenecks, limited financing, inadequate infrastructure, and insufficient technical capacity [106]. Overcoming these barriers requires coordinated reforms that encompass policy innovation, targeted financial incentives, capacity building, and the strengthening of public-private partnerships. The building sector also presents notable potential for energy savings, with frameworks such as the Building Energy Efficiency Guide for Nigeria advocating bioclimatic architectural design to enhance thermal performance and reduce demand [154]. A systematic framework combining interviews, measurements, and simulations has further underscored the importance of stakeholder collaboration in embedding energy-efficient practices into residential housing designs. Overall, while Nigeria's EE and RE potential is substantial, unlocking these opportunities depends on holistic strategies that integrate EMSs, expand the adoption of EETs, and accelerate RES deployment. Such approaches, reinforced by sustainable financial models, robust policy support, and multi-stakeholder collaboration, are essential to transform Nigeria's energy landscape and advance its sustainable development agenda.

Global policy implications: integrating energy efficiency into national and international climate goals

Integrating energy efficiency (EE) into national climate policies is vital for maximizing emission reductions and promoting economic growth, yet EE often remains underrepresented in global frameworks that prioritize economy-wide targets over sector-specific measures [162]. For example, Bangladesh's climate policies have shown limited success in aligning renewable energy (RE) and EE with national development goals [163], while studies on small open economies in the European Union reveal that although EE investments in building stock can increase GDP and employment, they may inadvertently drive higher energy consumption if not carefully managed [164]. Fig. 8 shows Nigeria's electricity policies, highlighting the goals and critical aspects. This highlights the need for balanced policy frameworks, especially as some national strategies prioritize RE sources such as biomass over EE technologies, contradicting the EU's "EE first" principle and leading to suboptimal emission reduction outcomes [121]. Evidence from Italy underscores the economic potential of robust EE policies, with projections estimating a €380.36 billion increase in final demand by 2030 under scenarios where EE serves as the primary driver of decarbonization [165]. Similarly, environmental taxation has emerged as a critical policy tool, with a U.S. study employing a putty-clay model of directed technical change suggesting that a 6.9-fold increase in energy taxes by 2055 would be required to meet Paris Agreement targets, thereby reinforcing the role of taxation in incentivizing EE and reducing emissions [166].

Interpolating strategic integration of energy efficiency in Nigeria

Major opportunities and threats

As of 2015, biomass accounted for 43 % of Nigeria's primary energy supply, as illustrated in Fig. 9 (a, b), while oil held a comparable share [168]. Natural gas and hydropower dominate on-grid generation, with gas stations supplying 86 % and hydropower 14 % [23]. The agricultural sector's demand remains low due to limited mechanization [169]. Political instability, however, poses a major threat to energy transition. Frequent leadership changes often delay or reverse earlier commitments, as seen when Nigeria revised its net-zero timeline from 2050 to 2060. While political stability could attract foreign and domestic investment, interruptions in governance have already hindered international cooperation [11].

Nigeria's scale presents opportunities: with a projected population exceeding 400 million by 2050 [170], the country has vast potential for solar, hydropower, and bioenergy [91,171]. The decline in the share of crude oil in Nigeria's primary energy mix by 2050 will be offset by the increasing utilization of natural gas and renewables. Natural gas shows promise for being a low-cost energy resource, with expected growth during the modeling time frame [172,5]. Natural gas is expected to play a pivotal role in the transition due to abundant reserves of 208.83 trillion cubic feet, sufficient for nearly a century of demand [173]. This reserve could sustain the country's energy needs for the next 94 years. In alignment with the country's energy transition strategy, Natural Gas is poised to assume a pivotal role in Nigeria's pursuit of net-zero carbon neutrality by 2060 [93]. Despite a projected increase in coal's share of the energy mix, with expectations of its rise from 5 PJ in 2015 to 39 PJ in 2030 and 696 PJ in 2050, its contribution to the overall energy composition is anticipated to remain relatively modest, constituting around 1 % by 2030 and 6 % by 2050. This limitation arises primarily due to the country's limited domestic utilization of coal resources. Some commentators argue that concerns regarding the cleanliness and sustainability of energy sources should not hinder development priorities. This perspective is further reinforced by a comparison of Nigeria's per capita CO2 emissions, which stands at 0.54t, in contrast to the United States' considerably higher 12.96t This argument is bolstered by the assertion that Nigeria possesses substantial natural coal reserves, amounting to 379 million tons, while maintaining a relatively low contribution to global GHGEs [174]. Plans for coal plants, such as the 60MW Okpella facility and six additional government-backed plants [175], risk undermining Nigeria's carbon neutrality targets.

Security concerns also threaten renewable adoption. Theft of batteries from solar streetlights and telecom base stations has discouraged investments, highlighting the need for improved protection [176]. Technology transfer remains limited due to the absence of local solar panel manufacturers, underutilized lithium reserves, and foreign exchange volatility, which inflate renewable costs [177,178]. Additionally, in areas where maintenance costs are closely monitored and prioritized, renewables have proven advantageous. The expenses associated with servicing diesel and gas generators can be eliminated by deploying renewables. This benefit has been leveraged to reduce operational costs, implement load-shedding strategies, and enhance operational efficiency. Notably, the game-changing aspect of renewables, particularly solar energy, is their low maintenance requirements and the absence of greenhouse gas emissions [179]. Apart from occasional battery replacements or rare instances of panel damage requiring intervention after several years of use, the initial investment cost is outweighed by the ongoing operational cost savings after deployment [180]. As illustrated in Fig. 10, the energy trend associated with solar technology deployment in Nigeria, spanning 11 years from 2012 to 2022, demonstrates a consistent increase, beginning at 15MW in 2012 and reaching a promising 37MW in 2022. In contrast, the country's total RE capacity, as depicted in Fig. 11, has remained relatively stable, fluctuating within the range of 2.12 to 2.16 over the same timeframe [181]. Innovative financing models, such as installment-based solar solutions from Auxano, Solynta, MTN, Easybuy, and Arnergy, have improved access for households and SMEs. These approaches reduce upfront costs and expand electrification while stimulating private investment [18]. Expanding such models with support from regional financial institutions could accelerate adoption further.

In summary, Nigeria's integration of energy efficiency and renewable is shaped by both opportunities—resource abundance, market size, and innovative financing and threats, including political instability, infrastructure insecurity, and coal expansion. Addressing these barriers through stable governance, security assurances, and technology transfer will be crucial for realizing the country's carbon neutrality ambitions [182,7].

Future trend

Given key macroeconomic factors, it is expected that Nigeria will experience a significant increase in the demand and use of various energy resources by 2030 and 2050. The total primary energy supply is projected to rise, reaching 5138 petajoules (PJ) by 2030 and 13,044 PJ by 2050. This represents a remarkable five-fold increase over 35 years, driven mainly by the country's substantial economic and population growth. In 2015, bioenergy was the leading energy source; however, a shift is anticipated, with its share decreasing from 43 % in 2015 to 33 % by 2030 and further falling to 27 % by 2050. In terms of supply, bioenergy is expected to grow from 1129 PJ in 2015 to 1622 PJ by 2030 and reach 3478 PJ by 2050 [23]. Concurrently, the proportion of crude oil within the energy supply matrix is poised for a nuanced shift, ascending from 41 % in 2015 to 45 % by 2030, only to recede to 33 % by 2050. This transformation is emblematic of the evolving energy landscape. Figurative representation, as illustrated in Fig. 9, underpins the emergence of "other renewables" as a burgeoning energy segment, escalating from a mere 17 PJ in 2015 to approximately 161 PJ by 2030 and a remarkable 512 PJ by 2050. Consequently, the share of "other renewables" within the primary energy composition is expected to exhibit a modest yet noteworthy progression, elevating from less than 1 % in 2015 to approximately 3.5 % by 2030 and a more conspicuous 4.3 % by 2050 [183,184]. These trends underscore the transformative dynamics shaping Nigeria's future energy sector, emphasizing the growing role of renewables and the evolving composition of its energy mix.

The adoption of Building Integrated Photovoltaic (BIPV) is gradually gaining momentum within the Nigerian construction sector [185]. This trend is notably observed as corporate entities increasingly embrace solar technologies to fulfill their energy needs, advance sustainability initiatives, and enhance the aesthetic appeal of their corporate facilities. Integrating solar power generation systems into various architectural elements such as roofs, parking areas, walls, windows, and facades is a functional and innovative design approach. This emerging trend promotes recognizing solar technologies as valuable assets, facilitating cost-saving strategies, and rendering them eligible for financial support from lending institutions [186]. As financial institutions and banks progressively reassess their lending criteria for solar technologies, deeming the associated funding risks as manageable and streamlining the access to capital for sustainable energy providers, we anticipate significant advancements in the implementation of BIPV systems in both public and private infrastructure projects [187,188].

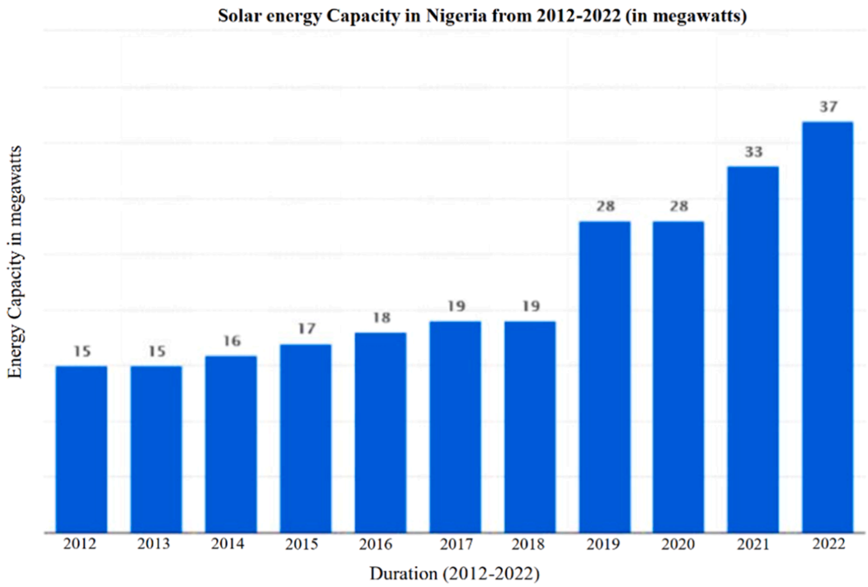

Fig. 10. Solar energy capacity in Nigeria from 2012 to 2022.

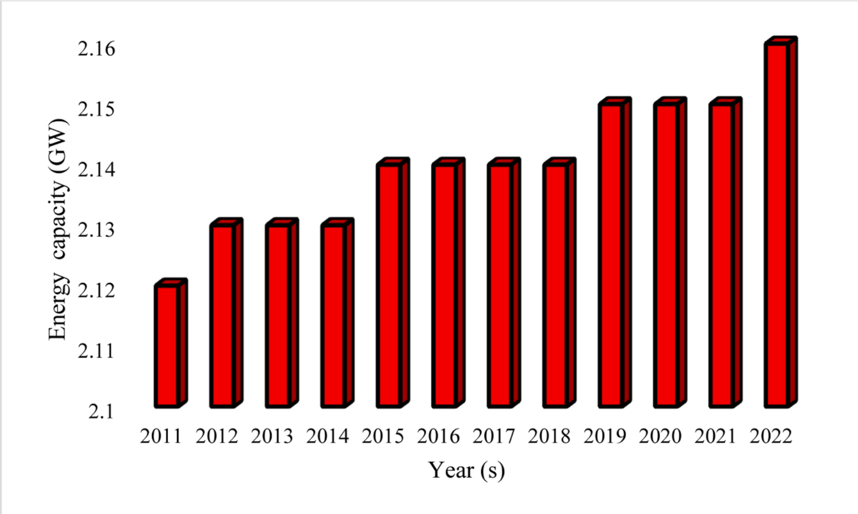

Fig. 11. Total RE capacity in Nigeria from 2011 to 2022.

A comprehensive examination of the impact of global fuel price dynamics on Nigeria's energy landscape reveals a significant surge in the adoption of SE as a primary power source. This shift represents a notable achievement in the context of RE deployment, considering the compounding factors of the COVID-19 pandemic, the Russia-Ukraine conflict, and the central bank's devaluation of the Naira, which collectively led to a quadrupling of diesel prices within four years. The situation was further exacerbated by removing fuel subsidies on premium motor spirit (PMS), rendering solar technology the most cost-effective alternative, and aside from the initial acquisition expenses. The 2020 IRENA report substantiates this assertion [195] findings, which reported a 13 % decrease in the global cost of Solar PV in 2019, culminating in a worldwide average cost of 6.8 cents per kWh. Comparatively, Nigeria's minimum cost of 0.487 USD stands notably higher, primarily attributed to the country's limited local production capacity for solar panels, absence of deep-cycle battery production, and consequently elevated importation costs for PV modules and batteries.

Mission and vision for Nigeria's carbon neutrality

As the most populous country in Africa, Nigeria has the potential to lead the continent and the world in reducing fossil fuel consumption and achieving low carbon emissions. A clear and purposeful mission is needed to achieve this goal, aligned with the nation's vision statement.

Mission

Nigeria's mission is to secure all the energy resources necessary for sustainable economic growth, including low-carbon emission sources. Clean cooking has been a significant issue in Nigeria for many years, and the government is on a mission to develop and promote high-energy-efficient, clean cooking solutions and provide access to modern forms of energy for the Nigerian people [189]. This takes a concise and clear mission by bringing more innovation to the energy infrastructure system. The mission of thriving industrialization for the whole country is a breakthrough for her societal welfare and the African region.

Vision

To meet the goals of the Paris Agreement and global climate governance, the Nigerian government has a clear and solid vision. It has prioritized securing green and energy-efficient solutions, in line with the green and sustainable Africa goals [190,191] and even the global goals. In partnership with local and international entities, including the Energy Commission of Nigeria, the Nigerian government has pledged to cut GHGEs by 20 % unconditionally and 47 % conditionally by 2030 to achieve net-zero emissions by 2060. Nigeria's push to expand the proportion of RE in its energy mix is widely recognized worldwide. The country aims to attain a carbon-negative status by 2100 by integrating more RE into sectors, including energy, building, transport, and agriculture, while tackling issues related to crude oil imports and GHGEs. For instance, the possibility and practicability of this vision have been compared with the present and future scenarios in Table 7, considering the progress of renewable-integrated energy sectors. These long-term goals will help Nigeria become a practical leader for Africa and the world. The Nigerian vision towards sustainability among the country's lawmakers, policy, and stakeholders consists of key elements, as elaborated in Fig. 12.

Strategic mindset, targets, and strategic focus for Nigeria's energy transition

Nigeria is making increasingly ambitious climate commitments, including a net-zero pledge. The country's think tanks recognize the significant challenges that arise from imbalances between energy supply and demand. These challenges are outlined in Fig. 13.

i. The mindset of Nigeria is focused on developing a proper energy infrastructure.
ii. To build a complete energy system, relatively low carbon.
iii. Increasing production of clean energy resources, including solar and wind, and efficient biofuels.
iv. Improving FFs technology and bringing further innovation in the fossil fuel industry.
v. Most of the transportation is diesel-based, and the policy think tank needs to have a mindset for including more EVs on roads in 2030 to 2050 scenarios.
vi. Clean energy cooking should be a top priority mindset, considering a new energy system.

A detailed examination of Nigeria's energy landscape reveals a concerning proximity to energy poverty. Data from a 2021 ESI-Africa report comparing the energy-to-GDP ratios of various countries underscores Nigeria's precarious position as it ranks lowest among nations with inadequate access to electricity. A staggering 86 million of its population lack access to electricity [192]. This situation is exacerbated by the nation's insufficient power generation capacity, coupled with a transmission and distribution infrastructure incapable of effectively conveying the total installed power if all generation stations were to operate at full capacity [193,194]. These challenges persist alongside issues related to price regulation, gas supply stability, and outstanding consumer utility bill payments. Addressing these concerns necessitates expanding the existing transmission infrastructure and a concerted effort by the government to attract investors across various segments of the power industry, including smart grids, energy storage device production, solar module manufacturing, and other related ventures. The Rural Electrification Agency (REA) and the Ministry of Power are tasked, among other responsibilities, with facilitating rural electrification and the development of infrastructure to extend electricity access to smallholder farmers' communities, satellite towns, and regions currently excluded from the national electricity grid [195]. Additionally, these agencies have championed adopting clean energy models for domestic cooking, particularly as a substitute for charcoal and firewood in rural areas. To change Nigeria's current statistics of poor electricity access, the REA must expedite efforts and employ a reliable strategy driven by RE.

In addition to these efforts, progress is evident in developing hydroelectric power plants (HEPs) such as Mambilla and Zungeru, which are currently under construction. Furthermore, the government's recent contract with Siemens Germany to revamp the nation's power industry is expected to yield positive results. However, progress has been sluggish, and the full benefits of the Siemens contract have yet to materialize. Upon completion, the Mambilla and Zungeru projects are anticipated to add 3,750MW to Nigeria's power grid, representing a significant step toward cleaner, sustainable, and self-replenishing energy sources [196]. However, improvements in transmission infrastructure are imperative to harness the potential of HEPs to their fullest capacity. The 04 anticipated new hydroelectric power plants, their capacity, and their expected completion year are described in Table 7. Moreover, advancements in fossil fuel technology are being driven by innovations such as Flue Gas Recirculation (FGR) technology and the conversion of vehicles from premium motor spirit (PMS) usage to liquefied petroleum gas. FGR technology reduces the volume of NOX emissions released into the atmosphere by boilers, promoting cleaner air and safer production practices, aligning with Sustainable Development Goals (SDGs) 3, 12, and 13. Establishing mega gas fueling stations and training artisans in the PMS-to-Gas dual-fuel conversion technique has enhanced fossil fuel technology prospects. Additionally, imposing high import tax tariffs on older vehicles indirectly incentivizes purchasing domestically assembled vehicles with improved fuel economy, reduced fuel consumption per mile, and lower greenhouse gas emissions [19].

However, the deployment of Electric Vehicles (EVs) for transportation has been slow, primarily due to the limited number of charging stations across the country and the relatively high prices of EVs, which place them beyond the reach of average income earners. This affordability gap hampers access to EVs for those who desire them, while high fuel prices are inconsequential to the upper class, given their higher net worth. The advantages of EVs, such as reduced or eliminated fuel-related expenses, lower maintenance costs, and noise reduction, are outweighed by the initial high costs unless more affordable options become available. In the interim, some users turn to hybrid cars when importing, allowing them to enjoy dual benefits and fuel flexibility. Furthermore, increasing the number of EVs on the road between now and 2030 is essential to ensure Nigeria remains on track to achieve the energy transition plan's 2060 targets [93,197]. Furthermore, awareness campaigns for clean energy must emphasize the health benefits and hazards of using charcoal and firewood. Many rural communities still rely on sawdust, charcoal, and firewood despite the availability of cleaner fuel options. Clean fuels often come with additional cost components, which can be prohibitive for rural dwellers who lack the necessary resources to afford them [189]. Notably, leading cement manufacturers in Nigeria, such as Dangote and Lafarge, have adapted their production processes to incorporate an energy mix that includes using Palm Kernel Shell (PKS) for kiln firing in clinker production [198]. Lafarge's Geo-cycle operations have enabled the production of eco-friendly cement with 30 % fewer carbon dioxide emissions, empowering building contractors and end-users to make environmentally responsible choices [199]. These incremental and disruptive changes have enhanced sustainability profiles, reinforced commitments to SDGs, reduced carbon footprints, and initiated decarbonization efforts within the cement manufacturing sector, setting a precedent for other major industrial players to follow. To

Table 7
Profile of new hydropower plant under construction.

S. No	Hydro Power Station	Name Plate Capacity (MW)	Expected Completion
1	Mambilla	3050	2027
2	Zungeru	700	2023
3	Makurdi	1650	2032
4	Lokoja	750	2033

Fig. 12. Key factors involved in the development of Nigeria's Vision.

Fig. 13. Nigeria's Strategic Mindset and call for Actions in the net-zero transition scenario.

sum up, Nigeria's energy transformation for the future necessitates concerted collaboration among the government, industry, and society, as well as broader international cooperation.

The strategic targets for net zero in 2030 and 2050 and even net-zero transition in various sectors, along with the necessary focus and actions to achieve, are briefly listed in Table 8.

Policy safeguard and implications (P-S-Is) for achieving Nigeria's net zero target emissions goals

Nigeria has a major opportunity to harness its abundant RESs to meet the growing needs of its population while tackling socio-economic issues. To realize this potential, a comprehensive set of policies across all sectors is required to guide the shift away from fossil fuels and promote financial and health benefits. RE technologies will be essential for creating a sustainable energy mix in Nigeria. The energy strategy must explore various transition routes, including electrification, the use of green gases, sustainable biomass, and solar thermal, alongside other vital infrastructure. To encourage the adoption of energy transition solutions and phase out fossil fuel technologies, a fiscal framework is necessary to deter new investments in these technologies and align with a climate-compatible future [202]. To support the adoption of transition-related technologies, policies and actions are needed to improve access to finance, encourage innovation, and increase awareness among consumers and citizens. The following sectors need incentives and significant policy interventions to assist Nigeria in reaching its strategic net-zero objectives.

Power sector

The power sector should aim to:

- Enhance the existing financing mechanisms and consider additional regulatory options.
- Encourage the development of creative financing solutions for both distributed RE and large-scale utility technologies.
- Replace diesel generators with standalone solar systems and MGs.
- Improve and broaden the regulatory framework for decentralized RE solutions.
- Speed up the electrification of end-uses and introduce policies to facilitate this process.
- Modernize the transmission and distribution infrastructure.
- Prioritize investment in RE over fossil fuel [203].
- Crystallize effort to kick start the green hydrogen project in Nigeria
- Introduce tax waivers for RE technologies to encourage imports and reduce upfront costs.

Building infrastructure

To improve building infrastructure:

- Build upon current efforts to promote clean cooking.
- Strengthen appliance efficiency and lighting programs.
- Introduce future government initiatives for improved cook stoves, broadening cooking alternatives through the use of modern renewable sources (including modern biofuels and electricity)[172].
- Leverage domestic expertise to re-engineer buildings to be suited for BIPVs.

Table 8
Strategic targets and key focus along with actions needed for net zero in 2030 and 2050.

Details of Resources and Sectors Involved	Targets accordingly currently planned Scenarios (CPS) 2030	Targets accordingly currently planned Scenarios (CPS) 2050	Strategic Focus and Necessary Actions for Net-Zero Targets
Share of RE in final energy case (includes traditional bioenergy)	43 %	40 %	A comprehensive and coordinated approach to energy transition planning is necessary to achieve a greater share of renewables in the energy sector. This should involve collaborating with multiple stakeholders across different sectors to promote modern renewables and reduce reliance on traditional bioenergy sources. Although traditional bioenergy use is projected to decrease as a share of energy demand, its actual consumption is predicted to increase by 2030 and 2050 unless alternative policies are implemented to address this trend.
Modern RE share in final energy (excluding traditional bio-energy)	8 %	10 %	
Share in Electrification (Final energy)	19 %	18 %	
Share of RE in power Production	36 %	42 %	1- Establishing collaborations with key stakeholders such as the CBN, the REA, and original equipment manufacturers can foster improved electrification and research and development. 2- Creating financing mechanisms for distributed RE and technologies such as microfinance can be beneficial. 3- Encouraging foreign and domestic direct investments can effectively enhance the country's development [200].
Gross Power generation capacity, Utility and Off-grid (GW)	56 GW	136 GW	
Solar	5 GW	25 GW	
Hydro (GW)	5 GW	25 GW	Developing and implementing RE infrastructure technology requires the transfer and capacity building of technology and skills [201].
BESS (GWh)	5 GW	25 GW	
Renewables in Transport	2 %	7 %	1- The development and deployment of renewable power infrastructure requires building and transferring technology and skills capacity 2- A financing mechanism needs to be developed for the infrastructure of all types of electric vehicles [197].
EVs Deployment	Nearly negligible, but could reach 2.8 million in the final transition scenario	Nearly negligible, but could reach 28 million in the final transition scenario	
Introducing Efficient and Modern bio-energy cook stoves for cooking purposes	6.5–12 million	21–33 million	1- To address the scaling-up and acceptability of clean cooking technologies, awareness campaigns must be created and implemented across all communities and regions. 2- Capacity building and training programs are necessary for home and community-based biogas digesters, particularly in terms of anaerobic digestion.
Cook stoves deployment in numbers	3–7.8 million	23–35 million	

Transportation sector

It is common knowledge that many transport firms are transitioning to gas-fueled buses and trucks. This implies progress for cleaner energy, as the government has recently announced the procurement of gas-fueled buses for mass transit to cushion the effect of fuel subsidy removal. To further transform the transportation sector, the following needs to be accelerated:

- Promote faster adoption of biofuels.
- Enforce policies focused on electrifying transportation and speeding up the adoption of electric vehicles (EVs)
- Encourage existing gas stations to co-locate EV charging stations, as the location is already in their favor.
- Enhance public transportation services and rail infrastructure using RE to achieve required modal changes and improve EE [197].

Industrial sector

The industrial sector should focus on:

- Developing local RE technology manufacturing industries.
- Improving EE in SMEs.
- Promoting the adoption of solar heating technologies [204].
- Increased capacity of waste conversion to energy and flue gas recirculation for secondary usage.

Policies for agriculture

To promote sustainable agriculture:

- Improve the affordability of solar irrigation pumps.
- Introduce policies to encourage the adoption of efficient pump sets.
- Provide incentives to promote the adoption of alternative fuel tractors [205,206].
- Set up wind turbines in the plateaus to harness the power generated by them for food processing and rural electrification.

Potential of the green hydrogen (GH) supply chain and its policies in Nigeria

GH, produced via electrolysis using RESs like solar and wind, has gained global attention as a key pillar of the energy transition towards a carbon-neutral future. Unlike grey hydrogen (produced from natural gas or coal) or blue hydrogen (which includes carbon capture technologies), green hydrogen offers a truly zero-emission alternative, making it an essential component in decarbonizing hard-to-electrify sectors, including heavy industry, long-haul transport, and aviation as depicted in Fig. 14.

Green hydrogen's potential lies in its versatility as a clean energy carrier that can be stored, transported, and used for various applications, from electric power production to industrial processes. However, realizing its full potential requires the development of a robust GH supply chain and supportive policies that encourage investment, innovation, and infrastructure development. Nigeria is

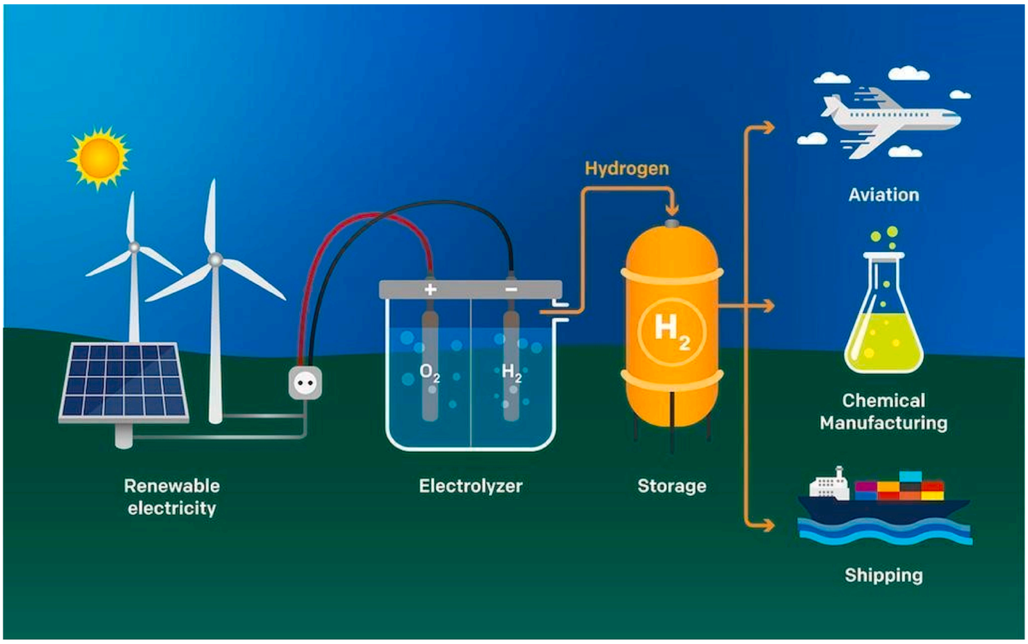

Fig. 14. The working principle of hydrogen production and its key utilization.

strategically positioned to leverage GH production to mitigate CC and enhance energy availability. While the country has been focusing on petroleum projects, there is a growing need to integrate green hydrogen production into its energy policies [207]. The potential for GH production from biomass waste in Nigerian cities, such as Kaduna, presents a significant opportunity to reduce CO2 emissions and achieve cost savings [208]. However, there is a lack of official hydrogen policies in Nigeria and the ECOWAS region, highlighting the need for regulatory frameworks to promote GH production and transition to a sustainable green economy [209]. Due to the abundant solar energy resources in the region, Nigeria has a significant opportunity to produce GH for domestic consumption and export. This can be achieved using the most cost-effective power sources available. As a result, policymaking needs to prioritize this opportunity. Industrial hydrogen use is one of the top priority end-uses, as indicated in Fig. 15, due to the absence of feasible alternatives in the short term. Additionally, the demand for hydrogen in industrial settings can be large enough to create economies of scale in production and infrastructure, making the transition to GH more cost-efficient in these applications [210,211].

Developing Nigeria's green hydrogen supply chain

To fully realize the potential of GH, Nigeria must develop a comprehensive supply chain that includes the following key components:

- Electrolysis Infrastructure: The heart of green hydrogen production is the electrolysis process. Scaling up electrolysis capacity requires significant investments in both technology and infrastructure. Nigeria's RE sector, particularly solar and hydropower, provides a strong foundation for building large-scale electrolysis plants in regions with high RE potential [212].
- Storage Solutions: Storing hydrogen is essential for balancing supply and demand. Hydrogen can be stored as a compressed gas, liquefied, or even in solid form using metal hydrides. While Nigeria has limited hydrogen storage infrastructure, there is potential to develop underground storage facilities in salt caverns, which are a cost-effective solution for large-scale hydrogen storage [213]. These storage solutions will be critical for ensuring the availability of hydrogen during periods of low RE generation.
- Transportation Networks: Hydrogen transportation, whether by pipeline, road, or sea, poses significant challenges due to hydrogen's low energy density and flammability. Retrofitting Nigeria's existing natural gas pipeline infrastructure to accommodate hydrogen could offer a cost-effective solution for domestic hydrogen distribution [214]. Nigeria's strategic location near Europe and the potential for green hydrogen exports by ship also make developing transportation infrastructure a priority.
- Hydrogen Refueling Stations: For the transportation sector, building a network of hydrogen refueling stations is essential for supporting the deployment of hydrogen-powered vehicles, including buses, trucks, and cars. Nigeria's transportation network and growing urban centers provide an ideal market for hydrogen fuel cell vehicles, especially in heavy-duty applications like buses and logistics [215].

Green hydrogen policies in Nigeria: current initiatives and future strategies

Nigeria's policy landscape for green hydrogen

As Nigeria works toward achieving its climate goals under the Paris Agreement, developing green hydrogen policies is essential for creating a regulatory environment that supports innovation and investment in the hydrogen economy. Nigeria's government has already signaled its commitment to RE through the RE Master Plan (REMP) [216] and the Energy Transition Plan (ETP) [217], which outline critical strategies for increasing the share of renewables in the energy mix.

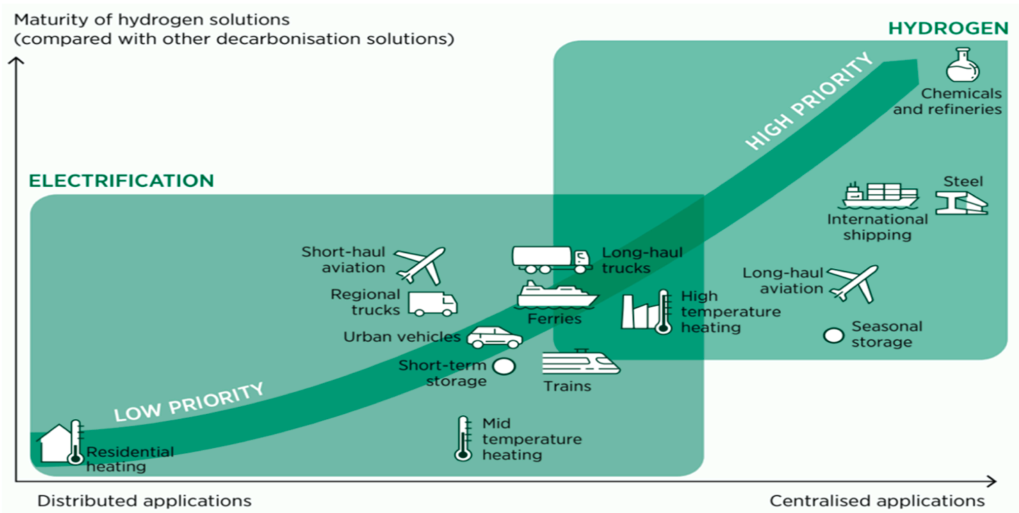

Fig. 15. Priority level based on Policies for Hydrogen.

However, specific policies tailored to green hydrogen are still in the early stages of development. Drawing lessons from other countries, Nigeria could implement policies that:

- Provide financial incentives for GH projects, including tax credits, subsidies, and low-interest loans for electrolysis and hydrogen infrastructure development.
- Set clear targets for GH production and use in specific sectors, including transport, heavy industry, and power generation.
- Support public-private partnerships to accelerate the deployment of hydrogen technologies and attract international investment.
- Ensure alignment between green hydrogen development and Nigeria's broader industrial policy, creating opportunities for local job creation and economic diversification.

International collaboration and climate finance

Access to international climate finance and technical assistance will be critical to Nigeria's success in building a green hydrogen industry. The country can benefit from partnerships with international organizations, such as the Green Climate Fund (GCF) and the African Development Bank (AfDB), to secure funding for green hydrogen projects. Collaboration with countries leading the way in green hydrogen development, such as Germany and Japan, could facilitate technology transfer and capacity building [218,219].

Opportunities and challenges for green hydrogen in Nigeria

Opportunities

- Regional Leadership in Hydrogen Production: Nigeria's abundant RE resources allow it to become a leader in GH production for domestic consumption and export to regions including Europe and North Africa [218].
- Decarbonizing Industry and Power Generation: Nigeria can significantly reduce its industrial emissions by replacing grey hydrogen and natural gas in key industries. Additionally, blending hydrogen with natural gas in power plants could offer a transitional solution while green hydrogen capacity is ramped up.
- Job Creation and Economic Diversification: Developing a green hydrogen supply chain could create thousands of new jobs in Nigeria, from engineering and construction to operations and maintenance, while diversifying the economy beyond oil and gas [220].

Challenges

- High Upfront Costs: Developing green hydrogen infrastructure requires significant upfront investment, particularly in electrolysis plants and storage facilities. The high costs could hinder rapid deployment without adequate financial support.
- Infrastructure Deficits: Nigeria's energy infrastructure, including its power grid and natural gas pipelines, requires upgrades to support large-scale hydrogen production and distribution [221].
- Policy and Regulatory Gaps: The absence of thorough green hydrogen policies and regulatory structures in Nigeria may hinder the growth of the hydrogen economy. Simplified permitting procedures and clear regulations are crucial to drawing in investment [209].
- **Technical Expertise and Workforce Development:** Establishing a green hydrogen industry demands substantial technical knowledge in fields like electrolysis, hydrogen storage, and fuel cell technology. Nigeria must invest in education and training initiatives to cultivate a skilled workforce capable of supporting the expansion of this sector [222]. Collaborating with countries with advanced hydrogen industries, like Germany or Japan, could facilitate technology transfer and capacity-building efforts.
- **Access to Financing:** Securing the necessary capital to develop the green hydrogen supply chain is one of Nigeria's biggest challenges. The high capital costs associated with building electrolysis plants, storage facilities, and transportation infrastructure could limit the pace of green hydrogen development. To address this, Nigeria will need to tap into international climate finance mechanisms, including the Green Climate Fund (GCF) and other multilateral funding sources, to support the early-stage development of the hydrogen economy [223,224].

Case study: green hydrogen pilot projects in Nigeria

While Nigeria's green hydrogen sector is still in its nascent stages, several pilot projects showcase the country's potential to develop a robust hydrogen supply chain.

Pilot project 1: solar-powered hydrogen production in northern Nigeria

A pilot project in northern Nigeria, in collaboration with local universities and international partners, is focused on developing solar-powered hydrogen production using electrolyzers. The project aims to demonstrate the viability of producing green hydrogen in regions with high solar potential. Initial findings from the project show that northern Nigeria's solar resources could support large-scale hydrogen production, potentially supplying domestic industries and export markets [225].

Pilot project 2: hydrogen fuel cells for clean transportation in lagos

In Lagos, a green hydrogen pilot project has been launched to explore using hydrogen fuel cells in public transportation. The project involves converting diesel-powered buses to hydrogen fuel cells, providing a clean alternative for urban mobility. If successful, the project could pave the way for a broader rollout of hydrogen-powered vehicles in major cities across Nigeria, reducing air pollution and GHGEs from the transportation sector [208,226]. These pilot projects are crucial for building momentum in Nigeria's green hydrogen industry and demonstrating the technical feasibility of hydrogen as a clean energy solution. By scaling up these projects and integrating them with broader national energy strategies, Nigeria can position itself as a leader in Africa's emerging GH economy.

Limitations and scope of the study

Although this paper includes an end-to-end scenario-based assessment of Nigeria transitioning to carbon neutrality, it has limitations to be noted. First is that this analysis is based on secondary sources of information, like publications on literature, policy reports, and international agency reports, and thus may introduce uncertainties or gaps in data. Secondly, modeling is done using pre-existing technological and policy paths, such that innovation breakthroughs that are unplanned or shifts in the political dynamics or economy may change outcomes predicted. The third limitation is the fact that although this paper highlights the opportunity in green hydrogen, it lacks detailed techno-economic modeling of hydrogen supply chains and thus will need to be done through subsequent empirical analyses. Finally, although the outcome offers other developing nations with lessons, direct application is best done within Nigeria's context and thus needs to be generalized cautiously. Although these limitations are noted, the paper offers critical contributions and provides a strategic framework to stakeholders and policy actors. Future work should involve the inclusion of primary collection of data, advanced system modeling, and comparative cross-country examinations to test and elaborate further on these results.

Conclusion

Nigeria's pursuit of carbon neutrality through energy efficiency presents both challenges and opportunities for sustainable development. This study has emphasized the critical role of energy efficiency in reducing reliance on fossil fuels, improving energy security, and fostering economic growth, while also highlighting the potential of renewable energy sources such as solar, wind, and hydropower in reshaping the national energy landscape. Additionally, the study underscores the importance of green hydrogen in decarbonizing hard-to-electrify sectors and advancing Nigeria's 2050 carbon-neutral goals.

Academic contributions

This research makes three key contributions to the academic literature:

1. Integrated Framework: It advances an integrated analytical framework that combines energy efficiency, renewable energy, and green hydrogen into a unified roadmap for achieving carbon neutrality, moving beyond the sectoral focus of most previous Nigerian studies.
2. Contextualized Policy Insights: By synthesizing global best practices with Nigeria's socio-economic and institutional realities, the study provides a novel case-based perspective on how developing countries can adapt international strategies to local contexts.
3. Scenario-based Road mapping: The paper introduces a mission, vision, and sectoral policy safeguard framework (across power, industry, transport, buildings, and agriculture) that can guide both academic debate and policy development regarding low-carbon transitions in emerging economies.

Policy and practical implications

Beyond academic contributions, the study identifies key enabling factors for instance, international climate finance, decentralized renewable systems such as solar mini-grids, and consistent policy implementation through public-private partnerships that are essential to accelerating Nigeria's transition.

Recommendations for future research

This paper presents an in-depth analysis of energy efficiency and carbon neutrality strategies in the Nigerian case; however, some emerging and insufficiently studied areas present great opportunities for additional study. Based on the current analysis, the following innovation-based prospective research directions are presented to further enhance both scientific study and practical application:

1. Green Hydrogen Production from Associated Petroleum Gas (APG) Flaring: Nigeria loses more than 7 billion cubic meters of natural gas each year to the atmosphere and is a significant source of greenhouse gas (GHG) emissions [207]. Follow-on studies should evaluate the viability of converting this excess methane to green or blue hydrogen through steam methane reforming (SMR) combined with carbon capture, utilization, and storage (CCUS), or by electrolysis energized by stranded solar energy assets in the Niger Delta. There is a need to carry out pilot-scale techno-economic and life-cycle assessment (LCA) investigations to establish the environmental and economic viability of these hybrid systems.
2. AI-Driven Digital Twins for Smart Grid and Mini-Grid Optimization: Although digital technologies such as digital meters and EMSs are well-established [159], few studies address AI-driven digital twins customized to Nigeria's decentralized energy systems. It is

possible to design dynamic simulation models in the future to incorporate real-time grid information, weather information, and load information to improve energy dispatch in off-grid solar mini-grids and improve reliability and EE in rural areas.

3. Retrofitting Urban Buildings with BIPV and Passive Design in Tropical Climates: Since Nigerian urban centers present very high cooling demands, the literature should concentrate on optimizing Building-Integrated Photovoltaics (BIPV) combined with passive cooling strategies like evaporative facades, thermal insulation, and natural ventilation to mitigate HVAC needs. Case analyses of government buildings (e.g., schools, hospitals) might evaluate energy reductions, payback periods, and scalability.
4. Behavioral Energy Efficiency in Rural Electrification Programs: Most EE policies are based on assumptions of rational user behavior, but energy usage is affected by cultural, economic, and educational considerations. Future research should design behavioral science frameworks (e.g., Nudge Theory) to explore adoption challenges of upgraded cook stoves, solar dryers, and energy-saving appliances among rural households to design more effective intervention strategies [206].
5. Hydrogen-Ready Gas Pipeline Retrofitting for Future Fuel Switching: Since natural gas infrastructure already exists, it is crucial that science considers the technical viability of Nigeria's pipelines to their blending with hydrogen (to levels of 20 %) or total transport conversion to hydrogen. Inspired by global endeavors [214], such analyses might consider material degradation, compression requirements, and safety requirements adapted to local conditions.
6. Circular Economy Integration in Industrial EE: The industrial sector has a huge untapped opportunity through waste-to-energy facilities and flue gas recirculation [204]. The future agenda should investigate circular economy paradigms in which waste heat from steel or cement plants energizes nearby agro-processing units through hybrid biomass-solar systems to develop local low-carbon industrial clusters.
7. Policy Coherence and Institutional Capacity Modeling: Regardless of multiple energy policies, enforcement is poor owing to institutional fragmentation. System dynamics modeling upon the work of Shari et al. [157] might be used to simulate how reforms in governance, inter-agency collaboration, and alignment in incentives affect EE program achievement rates over time.

These lines of inquiry embrace both technology and policy gaps and are long-term development aims in Nigeria on the topics of employment creation, energy access, and climate resilience. By focusing on context-specific and interdisciplinary investigations, scientists will be crucial in propelling Nigeria towards a sustainable, carbon-neutral future.

Declaration of competing interest

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

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