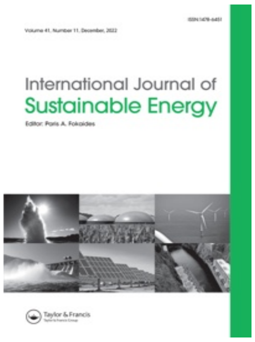
Low/zero carbon technology diffusion and mapping for Nigeria's decarbonization



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Low/zero carbon technology diffusion and mapping for Nigeria's decarbonization

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ABSTRACT

In pursuit of net-zero greenhouse gases emissions goals, Nigeria faces challenges like fossil fuel dependence, environmental degradation and energy inefficiency, necessitating a transition to decarbonization. This study employs the Bass model and TOPSIS multi-criteria analysis to investigate the diffusion and ranking of low/zero-carbon technologies for Nigeria. Findings reveal: absence of key mitigation technologies like wind, concentrating solar plant (CSP), geothermal, nuclear, hydrogen, fuel cell, carbon capture utilization and sequestration (CCUS), direct air capture (DAC), and lime soda in Nigeria; that over a fifty-year span from year 2023, existing technologies–solar photovoltaic, bioenergy, natural gas and hydro–in Nigeria indicate slow adoption rates (3.68–106.02MW) based on Nigeria trajectory of technology use, contrasting with significantly accelerated rates (276.06–90,320MW) based on global trajectory; and multi-criteria analysis favors hydro, solar photovoltaic, natural gas, bioenergy, and wind as favorable options, while suggesting further exploration of hydrogen, fuel cell, geothermal, and nuclear technologies within Nigeria's energy landscape.

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Low/zero carbon technologies; technology diffusion; decarbonization; multi-criteria analysis; TOPSIS

1. Introduction

The impact of climate change can be viewed as a complex and multifaceted global challenge affecting ecological, environmental, sociopolitical, and socioeconomic domains (Filho et al. 2021; Feliciano et al. 2022; Abbass et al. 2022). Due to its significant effects on the Earth's ecosystems and human societies, global climate change is an urgent topic that has drawn considerable attention. Human activities are primarily responsible for significant shifts in the Earth's climate system. As a result, climate change's consequences are becoming ever more evident and alarming. A key aspect of its characterization is assessing the long-term patterns of temperature and precipitation, along with factors such as atmospheric pressure and humidity (Abbass et al. 2022). Climate change has been linked to a number of escalating effects and hazards, such as increased storm activity, depleted ecosystems, and unprecedented heatwaves. Aside from irregular weather patterns, global ice sheets melt which causing sea levels to rise, are globally recognized and domestically observed consequences of climate

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change (Lipczynska-Kochany 2018; Murshed and Dao 2022). Although once considered bearable, the rise of global mean surface temperature (GMST) by 2.0°C or more compared to the pre-industrial era is now considered unmanageable and dangerous to both natural and human systems (Hoegh-Guldberg et al. 2019). With global climate change posing more challenges than ever before, cutting carbon dioxide emissions is becoming urgent worldwide (Murshed and Dao 2022).

Global efforts toward decarbonization have significantly accelerated in response to the growing worries about climate change and its negative consequences on the environment. Decarbonization, which can be describes as the reduction of greenhouse gases (GHGs) and the transition to cleaner and more sustainable energy sources (Virta 2023; The Welding Institute 2023), has become a paramount objective for governments, organizations, and societies worldwide. The Paris Climate Agreement is a major and the most recent effort to promote international cooperation on climate change. This agreement, which 185 countries have signed or joined, intends to bring nations together voluntarily to take significant steps to reduce climate change. In addition, it highlights how crucial it is to ensure that the essential resources are available for implementation, such as climate finance, as well as the need of developing adaption approaches and strategies (Hoegh-Guldberg et al. 2019). According to reports, the energy industry will need to make a large financial investment if global warming is to be limited to 1.5°C. In particular, between 2016 and 2050, it is projected that investments in energy supply measures will range from $1.46 trillion to $3.51 trillion (in US dollars 2010), while investments in energy demand measures will range from $640 billion to $910 billion. The achievement of the goal of net zero greenhouse gas emissions by 2050 depends on these expenditures (Intergovernmental Panel on Climate Change 2019). A number of global efforts towards decarbonization have been identified through literature, underscoring the collective commitments of the global community to decarbonization and addressing the challenges of climate change. These initiatives cover a wide range of actions and strategies such as the following (Krishnan et al. 2023; International Energy Agency 2021; Rissman et al. 2020; Cames et al. 2021; Chen et al. 2022): (i) Encouraging the switch from fossil fuels to electricity with zero emissions and other low emission energy sources, such as hydrogen, in order to change the energy mix (ii) Implementing decarbonization measures in industrial and agricultural processes; (iii) Prioritizing energy efficiency and efficient demand management; (iv) Implementing circular economy principles for sustainable emissions reduction; (v) Consuming fewer emission-intensive goods; (vi) Recognizing the necessity of significant investments in clean energy; in order to achieve net-zero emissions by 2050, the annual global investment in clean energy must triple to approximately $4 trillion by 2030; (vii) Emphasizing rapid deployment of existing technologies and the development of new technologies to align with the net-zero target; (viii) The emergence of a growing coalition of countries, cities, businesses, and other institutions that are steadfast in their commitment to achieving net-zero emissions; (ix) Formulation of national climate action plans that emphasize emission reductions and climate change adaptation; and (x) implementing measures to reduce emissions in the power and transportation sectors, such as boosting the use of renewable energy sources, aiming for zero-emission vehicles by 2030, and pushing for the decarbonization of global shipping.

Technology significantly contributes to decarbonization by offering innovative solutions for reducing greenhouse gas emissions and transitioning to sustainable energy systems (Wang et al. 2021). Renewable energy is one important area where technology plays a critical role (Sen and Ganguly 2017; Vo et al. 2020). Decarbonization has been considerably aided by the development and application of renewable energy technologies like solar, wind, hydro, and geothermal power. With the use of these technologies, power can be produced with little or little emissions, lowering the need for fossil fuels and the energy sector's carbon footprint (Gielen et al. 2019; United Nations 2023). Energy storage technologies, like batteries, pumped hydro, and thermal storage, are crucial for decarbonization by bridging the gap between renewable energy production and demand, enhancing reliability and stability (Tan et al. 2021; Wang et al. 2022). Transport technology advancements are crucial for decarbonization in addition to energy-related ones. Alternative fuels such as hydrogen fuel cells, electric vehicles (EVs), and others provide cleaner, more environmentally friendly transportation options that help to reduce the need for fossil fuel-powered cars and the emissions they produce (Sandaka and Kumar 2023; Çabukoglu et al. 2019; Pustějovská, Janovská, and Jursová 2023). Additionally, data analytics and digital technologies are essential for enhancing energy management, maximizing energy systems, and facilitating well-informed decision-making. The efficiency and adaptability of the energy system are improved by the use of smart grids, Internet of Things (IoT) gadgets, and advanced data analytics to monitor energy usage, optimize energy distribution, and enable demand response programs (Li et al. 2022; Saleem et al. 2023; Sadeeq and Zeebaree 2021). Overall, technology acts as a catalyst for decarbonization by offering ways to cut emissions, boost energy efficiency, enable the integration of renewable energy, and push different sectors towards a sustainable, low-carbon future (Rissman et al. 2020; Wang et al. 2021).

Nigeria's energy landscape is predominantly fueled by fossil sources like oil and natural gas, historically serving power generation, transportation, and industrial needs. While Hydropower remains a primary renewable source, its capacity is limited, whereas solar is rapidly expanding, albeit still constituting a small share of the overall energy mix of the country. In comparison to the rest of the world, Nigeria's adoption of renewable energy has been relatively modest, with fossil fuels maintaining dominance (Olujobi et al. 2023). Globally, there is a noticeable shift towards a more diversified energy mix, with renewables (hydro, wind, solar) witnessing rapid growth (Hassan et al. 2023). Regional variations are evident with developed nations exhibiting higher renewable shares, while developing countries, like Nigeria, heavily rely on dirty fuels (e.g. fossil and crude biomass). Nigeria's renewable status is characterized as thus: (i) low and slow penetration – contributing less than 16.4% (with over 90% from hydro) to total electricity capacity as at 2022 (Statista Research Department 2024); (ii) ambitious policy goals – targeting 30% renewable electricity generation by 2030 (Ajala 2024) and net-zero emissions by 2060 (Ogbonna et al. 2023); and (iii) associated challenges like infrastructure gaps, financing hurdles, and grid integration issues that could hinder growth. On a global scale, renewables account for about one-third of electricity generation (Our World in Data 2024) and is rapidly growing. Nigeria's commitment to transitioning to a low-carbon economy is evident and emphasized in net zero pledge and a number of National climate change/decarbonization documents (Okoh and Okpanachi 2023). Abundant resources, a large population, and a rising demand for clean energy underscore the importance for Nigeria to explore its low carbon and clean energy potential. The recent passage of the Electricity Act 2023 marks a pivotal moment, ushering in an era focused on sustainable power sources and technological advancements in the realm of renewable energy (United Nations Conference on Trade and Development 2024).

Towards addressing climate change and transitioning to a low-carbon economy, Nigeria has been making efforts to decarbonize. Some key aspects of Nigeria's efforts to decarbonize can be seen in the area of pushing for renewable energy development. Nigeria recognizes the importance of renewable energy sources in decarbonization, such as solar, wind, biomass, and hydropower, and has been actively promoting initiatives like the Nigerian Renewable Energy and Energy Efficiency Project (NREEEP), and the Renewable Energy Master Plan (REMP) aimed at increasing the share of renewable energy in the country's energy mix. The goal of Nigeria's Renewable Energy Master Plan (REMP) is to gradually increase the share of renewable electricity in the country's overall energy mix. The plan establishes goals for renewable electricity generation, increasing from 13% in 2015 to 23% by 2025 and 36% by 2030. For different renewable energy sources, such as small hydro, solar PV, biomass-based power plants, and wind, the REMP also specifies capacity targets. The plan also emphasizes increasing electrification rates, with goals of 60% by 2015 and 75% by 2025, up from 42% in 2005. The REMP also includes a variety of financial and market incentives to assist the adoption of renewable energy (International Energy Agency 2023a; International Energy Agency 2023b).

The Nigerian government created the National Renewable Energy and Energy Efficiency Policy (NREEEP) to promote the use of renewable energy sources and improve energy efficiency across the country. By encouraging the sustainable use of renewable energy sources and putting energy-efficient practices in place, this strategy was created to address Nigeria's problems with the country's energy supply. The NREEEP seeks to accomplish a number of goals, including enhancing energy security, reducing greenhouse gas emissions, and promoting economic growth. The NREEEP aims to offer a planned and efficient solution to Nigeria's energy demands by increasing access to electricity, lowering energy poverty, and creating job opportunities in the renewable energy sector (Sengupta 2023; Federal Ministry of Power 2023).

Nigeria has expressly declared its commitment to attain net-zero greenhouse gas emissions by 2060, as expressed in various official documents and initiatives, aligning with President Muhammadu Buhari's explicit pledge at the 2021 Conference of Parties (COP26) in Glasgow (Ogbonna et al. 2023; Climate Action Tracker 2022). This initiative include the Climate Change Act enacted in 2021 that establishes a legal framework for climate action, articulating the overarching objective of attaining net-zero emissions within the timeframe of 2050–2070. The legislation mandates the formulation of National Climate Change Action Plans in five-year intervals, serving as comprehensive guides for the implementation of emissions reduction strategies (National Council on Climate Change 2024). Aside from addressing challenges in implementation, transparency, and financing (Ogbonna et al. 2023; Dioha 2023), the crucial task of simultaneously ensuring affordable and reliable energy access for all Nigerians while reducing emissions is a significant concern, necessitating careful consideration in the adoption of appropriate technologies.

Nigeria submitted its Nationally Determined Contribution (NDC) in accordance with the Paris Agreement, which specifies the nation's climate change mitigation and adaptation objectives, to demonstrate its efforts toward decarbonization. Nigeria's updated NDC targets to reduce economy-wide emissions conditionally by 47% and 20% unconditionally by 2030 (NDC Partnership 2023). It also commits to end flaring by 2030 and reduce fugitive methane emissions from oil and gas operations by 60% by 2031 (Climate Action Tracker 2023; International Energy Agency 2023c). In addition to mitigation targets, Nigeria's NDC highlights several key points. Firstly, it stresses the promotion of renewable energy sources such as solar, wind, hydro, and biomass to diversify the energy mix and lessen dependency on fossil fuels. Secondly, in recognition of Nigeria's sensitivity to climate change, the NDC also specifies adaptation methods such as enhancement of climate resilience in agriculture, water resource management, and urban infrastructure. Thirdly, it emphasizes the importance of halting deforestation and forest degradation. Lastly, the NDC addresses cross-cutting themes like gender, youth, capacity building, public awareness, and institutional strengthening, which are crucial for effective climate action and sustainable development (Federal Government of Nigeria 2023).

The Energy Transition Plan (ETP) is another indication of Nigeria's decarbonization efforts. The Nigeria Energy Transition Plan (ETP) is a strategic roadmap aimed at necessitating substantial emission reductions in five crucial sectors in order to achieve carbon neutrality by 2060. The plan outlines a framework and timeline for implementing emission reduction measures across the Power, Cooking, Oil and Gas, Transport, and Industry sectors, which according to the ETP collectively account for approximately 65% of Nigeria's emissions. The ETP's main goals are to reduce emissions by 65%, alleviate energy poverty, foster investment opportunities, and improve energy efficiency. The strategy offers major investment possibilities in the fields of solar energy, hydrogen, and electric cars, each of which is anticipated to result in the creation of net new jobs (Nigeria Energy Transition Plan 2023). Other climate-relevant greenhouse gas (GHG) emissions and energy modelling studies which illustrates Nigeria's efforts to decarbonize include the Long-Term Low Emissions Development Strategy (LT-LEDS), Deep Decarbonization Pathway Project (DDPP), Nigeria Energy Calculator 2050 (NECAL 2050), as well as the Integrated Resource Plan (IRP).

Furthermore, one critical question to be asked is 'to what extent will technology be involved in the decarbonization effort in Nigeria?' To address the question, the study aims to conduct technology diffusion and mapping of various low/zero carbon technologies to support Nigeria to achieve its climate change mitigation ambition. The aim of the study is anchored on the objectives to investigate diffusion patterns and adoption rates of low/zero-carbon technologies considering both currently existing and potential technologies in Nigeria, evaluated in terms of both Nigeria and global trajectory of technology use; and to conduct multi-criteria analysis to rank the technologies and offering strategic insight in identifying favorable technology options for Nigeria's sustainable energy landscape. This research aspires to offer a comprehensive understanding of technology adoption trends thus serving as a foundational resource for policymakers, energy stakeholders, and climate advocates in Nigeria, ultimately accelerating the nation's transition to a low-carbon and sustainable future.

The paper comprises five key sections. First, the introduction sets the stage by reviewing climate change and decarbonization efforts worldwide and in Nigeria. The second section – methodology presents the analytical approach, i.e. utilizing the Bass model for technology diffusion and TOPSIS multi-criteria method for mapping. The third section is the results and discussion section, where the study's findings are presented and discussed in depth. Section four highlights critical findings and their implications. The paper concludes with section five, summarizing key takeaways and insights.

2. Methodology

In this section, the models used for a comprehensive analysis of technology diffusion and evaluation of low/zero carbon technologies are presented. The Bass model, a well-known framework for technology diffusion analysis, was used to analyze the diffusion characteristics of the highlighted technologies (Ratcliff and Doshi 2016; Turk and Trkman 2012). In addition, we use the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method, a multi-criteria analysis approach, to rank the identified low/zero carbon technologies according to different criteria. TOPSIS, with its ability to handle quantitative data and consideration of nuanced criteria, including economic, technical, environmental, and social factors, aligns seamlessly with the complexity and breadth of this study's dataset. This adaptability makes TOPSIS an ideal choice for robustly assessing and ranking the suitability of diverse low/zero carbon technologies for Nigeria's energy mix (Madanchian and Taherdoost 2023; Vavrek and Bečica 2022). The selection of the Bass model and TOPSIS method is driven by their proven effectiveness in examining technology diffusion patterns and facilitating decision-making processes through comprehensive multi-criteria evaluation. By combining these two analytical approaches, it provides a robust framework for understanding the diffusion dynamics and ranking of low/zero carbon technologies, thus contributing valuable insights to inform sustainable technology adoption strategies as it relates to Nigeria. The data collection process involved a combination of sources. To establish market potential (m) assumptions, demographic data, global average energy demand per capita and current energy and carbon statistics for Nigeria were gathered from reputable organizations. Information on the installed capacity of various energy generation technologies and carbon capture and removal technologies was sourced from international organizations, including the International Renewable Energy Agency (IRENA), International Atomic Energy Agency (IAEA), International Energy Agency (IEA), and others. The estimation of Bass model parameters (p, q) utilized least square regression to regress collated data, and this analysis was conducted within the integrated environment of Microsoft Excel. All other specific assumptions for the respective analyses are provided in their respective subsections. The flowchart (Figure 1) illustrates the comprehensive methodology employed in this article, outlining the systematic approach to technology diffusion analysis and multi-criteria evaluation for low/zero-carbon technologies in Nigeria's decarbonization process.

2.1 Technology diffusion analysis

In this subsection, the models employed to depict the technology diffusion patterns of the chosen low carbon technologies are presented. The process of technology adoption over time typically exhibits an exponential trend, particularly resembling the S-shaped curve. This distinctive curve is characterized by an initial phase of slow growth or delay, succeeded by a rapid acceleration once a critical point is reached. Subsequently, the growth rate gradually stabilizes, reaching a saturation

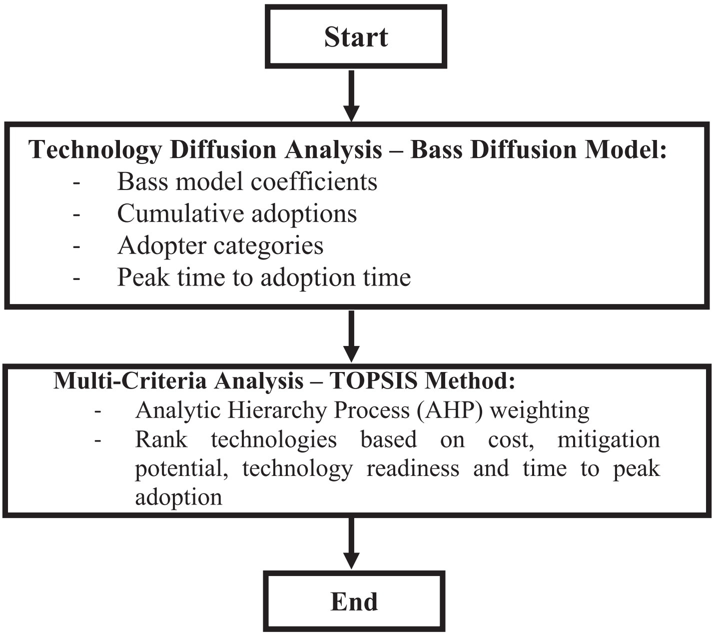

Figure 1. Methodology overview.

point known as the carrying capacity. Finally, a sudden surge occurs, representing a significant leap in adoption. This S-curve finds greater relevance in simulating the adoption patterns of low-carbon and/or renewable energy technologies (Schilling and Esmundo 2009; Purohit and Kandpal 2005). In this study, the Bass diffusion model is adopted to accurately capture and represent this type of growth. The Bass diffusion model holds significance as the pioneering quantitative model for new product diffusion and remains one of the most frequently referenced and extensively analyzed models in its domain (Fibich and Gibori 2010).

For simplicity of analysis the following model assumptions were adopted:

i. The diffusion process is binary (0) or (1), i.e. either adopt (1) or do not adopt (0)
ii. The adoption of the technology is influenced by two (2) fundamental types of behaviors – ‘innovation’ which is driven by influences such as advertising and ‘imitation’ which is influenced by word of mouth and/or interpersonal relationships;
iii. Maximum number of adopters or market potential is constant over the diffusion process;
iv. All potential adopters eventually purchase or adopt the technology /product;
v. Repeat and/or replacement purchases are not accounted for, thus one customer per product at each time ‘t’;
vi. There are no supply limitation of the technology/product;
vii. The diffusion process is not interrupted by the decisions and/or diffusion process of other innovations in circulation.

2.1.1 Mathematical formulations of the Bass model

The likelihood of adoption of a product/technology at time t given that no prior purchase has yet been made based on the Bass model is described by (Bass 2004; Lilien, Rangaswamy, and Bruyn 2007; Mahajan, Muller, and Bass 1995)

$$\frac{f(t)}{1-F(t)} = p + qF(t) \tag{1}$$

$$F(t) = \int_0^T f(t)dt \quad ; \quad F(0) = 0 \tag{2}$$

where $f(t)$ represents the probability density function which indicates the rate at which the probability of adoption changes with time t; $F(t)$ is the cumulative distribution function of adoption at time t, i.e. the cumulative probability that the target segment will adopt the technology by time t; p represents the coefficient of innovation or coefficient of external influence; and q is the coefficient of imitation or coefficient of internal influence.

Considering that

$$n(t) = mf(t) \tag{3}$$

$$N(t) = mF(t) \tag{4}$$

Equation (1) was further manipulated to give:

$$n(t) = \frac{dN(t)}{dt} = \left(p + \frac{q}{m}N(t)\right)(m - N(t)) \quad ; \quad (p, q \geq 0) \tag{5}$$

$$n(t) = \frac{dN(t)}{dt} = p(m - N(t)) + \frac{q}{m}N(t)(m - N(t)) \tag{6}$$

$$n(t) = pm + (q - p)N(t) - \frac{q}{m}(N(t))^2 \tag{7}$$

where $n(t)$ is the adoptions at time t; $N(t)$ is the cumulative adoptions at time t; m is the potential market size and/or ceiling; the term $p(m - N(t))$ and $\frac{q}{m}N(t)(m - N(t))$ in Equation (6) represents technology adoptions independent of the influence of previous users or buyers of the technology; and technology adoptions influenced by previous users or buyers of the technology, respectively.

Further manipulations of Equation (1) assuming $F(t = t_0 = 0)$ yields the following S-shaped cumulative adopter distribution function($N(t)$)

$$N(t) = m\left[\frac{1 - e^{-(p+q)t}}{1 + (q/p)e^{-(p+q)t}}\right] \tag{8}$$

For the S-shaped diffusion curve, expressions related to the peak point of adoption are given as:

$$T^* = -\frac{1}{p+q}\ln\left(\frac{p}{q}\right) \tag{9}$$

where T^* represents the time of peak adoption.

2.1.1.1 Estimating diffusion model parameters. In this work, a straightforward algebraic estimating approach as shown in this subsection, will be adopted to estimate the diffusion process parameters – coefficient of innovation (p), coefficient of imitation (q) and the market potential (m), respectively.

First step: Adopt an analogy by aspects strategy – which is an approach to estimating the Bass model parameters, p, q and m from data of historical sales of the product/technology or an analogous products (Ganjeizadeh et al. 2017).

Second step: Using least square regression method regress the collated data to obtain quadratic polynomial in the form in Equation (10)

$$y = a + bx + cx^2 \tag{10}$$

Third step: Equate Equation (13) to the Bass model relation presented in Equation (7), the parameters can then be resolved as follows:

$$p = \frac{a}{m} \tag{11}$$

$$q = p + b \tag{12}$$

$$m = \frac{-b - \sqrt{b^2 - 4ac}}{2c} \tag{13}$$

The market size (m) will be determined in this work for this forecasting process using an external procedure (such as a survey of long-term purchase intentions) to account for terrain peculiarities like population/target market volume, penetration rate, average cost of technology, etc., while the Bass parameters $'p'$ and $'q'$ will be estimated based on the relationships shown in Equations (11) and (12) in conjunction with $'m'$.

2.1.1.2 Determining adopter categories. Adopter of a technology based on the time of adoption can be categorized into the following groups, namely: innovators, early adopters, early majority, late majority and Laggards (see Figure 2).

Determining the respective adopter categories is dependent on knowing the inflection points T_1 and T_2, which are expressed analytically as follows (Mahajan, Muller, and Srivastava 1990):

$$T_1 = -\frac{1}{(p+q)} \ln\left[\left(2+\sqrt{3}\right)\frac{p}{q}\right] \tag{14}$$

$$T_2 = -\frac{1}{(p+q)} \ln\left[\frac{1}{\left(2+\sqrt{3}\right)}\frac{p}{q}\right] \tag{15}$$

Furthermore the analytical expressions for the respective adopter categories covered on the Bass adopter distribution are:

(a) Innovators

Time interval – Initiators of diffusion process
Expression for time interval:

$$\mathfrak{E}T_{IN_i} = \varphi \tag{16}$$

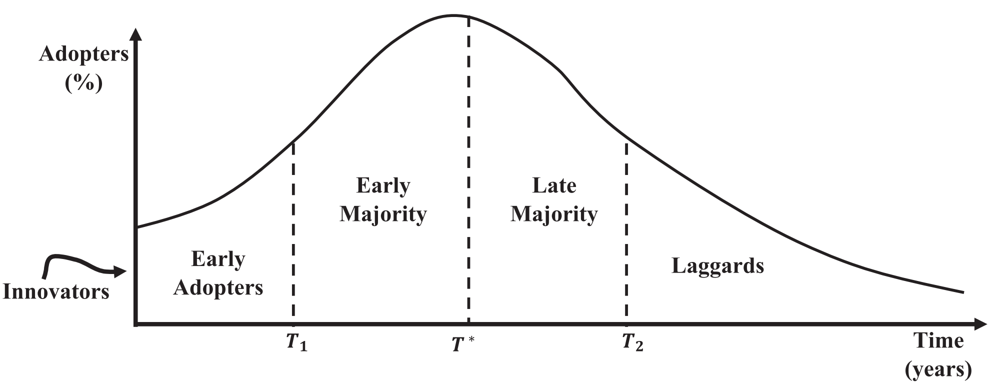

Figure 2. Adopter categories based on Bass diffusion model. Source: Mahajan, Muller, and Srivastava (1990).

where $\mathfrak{E}T_{IN_i}$ means expression for time interval for innovator category of the i-th technology; and φ means no expression or value.

Expression for adopter category size:

$$\mathfrak{E}\mathcal{A}_{IN_i} = p \tag{17}$$

where $\mathfrak{E}\mathcal{A}_{IN_i}$ represents expression for adopter category size for innovator category of the i-th technology

(b) Early adopters

Time interval – Up to T_1
Expression for time interval:

$$\mathfrak{E}T_{EA_i} = \frac{1}{(p+q)}\ln\left[\left(2+\sqrt{3}\right)\frac{p}{q}\right] \tag{18}$$

where $\mathfrak{E}T_{EA_i}$ represents expression for time interval for early adopters category of the i-th technology

Expression for adopter category size:

$$\mathfrak{E}\mathcal{A}_{EA_i} = \frac{1}{2}\left(1-\frac{p}{q}\right) - \frac{1}{\sqrt{12}}\left(1+\frac{p}{q}\right) - p \tag{19}$$

where $\mathfrak{E}\mathcal{A}_{EA_i}$ represents expression for adopter category size for early adopter category of the i-th technology

(c) Early majority

Time interval – T_1 to T^*
Expression for time interval:

$$\mathfrak{E}T_{EM_i} = \frac{1}{(p+q)}\ln\left(2+\sqrt{3}\right) \tag{20}$$

where $\mathfrak{E}T_{EM_i}$ represents expression for time interval for early majority category of the i-th technology

Expression for adopter category size:

$$\mathfrak{E}\mathcal{A}_{EM_i} = \frac{1}{\sqrt{12}}\left(1+\frac{p}{q}\right) \tag{21}$$

where $\mathfrak{E}\mathcal{A}_{EM_i}$ represents expression for adopter category size for early majority category of the i-th technology

(d) Late majority

Time interval – T^* to T_2
Expression for time interval:

$$\mathfrak{E}T_{LM_i} = \frac{1}{(p+q)}\ln\left(2+\sqrt{3}\right) \tag{22}$$

where $\mathfrak{E}T_{LM_i}$ represents expression for time interval for late majority category of the i-th technology

Expression for adopter category size:

$$\mathfrak{E}\mathcal{A}_{LM_i} = \frac{1}{\sqrt{12}}\left(1+\frac{p}{q}\right) \tag{23}$$

where $\mathfrak{E}\mathcal{A}_{LM_i}$ represents expression for adopter category size for late majority category of the i-th technology

(e) Laggards

Time interval – T_2 and Beyond
Expression for time interval:

$$\mathfrak{E}T_{LA_i} = \varphi \tag{24}$$

where $\mathfrak{E}T_{LA_i}$ means expression for time interval for laggards category of the i-th technology; and φ means no expression or value.

Expression for adopter category size:

$$\mathfrak{E}\mathcal{A}_{LA_i} = \frac{1}{2}\left(1+\frac{p}{q}\right) - \frac{1}{\sqrt{12}}\left(1+\frac{p}{q}\right) \tag{25}$$

where $\mathfrak{E}\mathcal{A}_{LA_i}$represents expression for adopter category size for laggards category of the i-th technology

2.2 Multi-criteria analysis

In this section the simple mathematical models employed to conduct the multi-criteria analysis of selected low-carbon technologies to obtain an optimal system ranking of technologies that facilitates the goal of achieving Nigeria's low carbon energy transition is presented. To accomplish this, a multi-criteria optimization technique called Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is used. This technique enables the identification of solutions from a finite number of alternatives by simultaneously minimizing the distance from an ideal point and maximizing the distance from a negative ideal point. Employing this methodology aids the synthesis of a ranking system based on attributes such as cost, mitigation potential, technology readiness, and technology diffusion. For simplicity of analysis using the TOPSIS methodology, the following assumptions were adopted:

i. Each decision-making criterion considers either monotonically increasing or decreasing preference;
ii. The criteria need to be given a set of weights;
iii. Using the appropriate scaling technique, every outcome that is expressed in a non-numerical form should be quantified.

2.2.1 Procedure/mathematical formulations of the TOPSIS methodology

In this subsection, the key steps in carrying out the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) analysis are presented. The application of TOPSIS will be as follows (Corrente and Tasiou 2023; Hwang and Yoon 1981; Pavić and Novoselac 2013; Tamošaitienė, Zavadskas, and Turskis 2013):

Step 1 – Create a decision-making matrix with 'm' alternatives and 'n' criteria

Consider a ranking problem in which the alternatives of $A = \{a_1, \ldots .a_m\}$ are evaluated on the criteria in $C = \{c_1, \ldots .c_n\}$ with the intersection of the alternative and criteria given as x_{ij} to form a matrix $(x_{ij})_{m\times n}$.

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad (26)$$

For visibility, the alternatives $(A_1, A_2, \cdots, A_m)$, criteria $(C_1, C_2, \cdots, C_n)$ and weights $(w_1, w_2, \cdots, w_n)$ are placed in an initial table as presented in Table 1.

Step 2 – Vector normalization

At this stage, each performance rating/value is divided by the norm of the total outcome vector of the criteria under consideration. This normalizing process facilitates easier value comparison by converting dimensioned units of respective attributes into dimensionless units. This is calculated by:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}} \quad (27)$$

where r_{ij} is the normalized ratings of each cell.

Step 3 – Calculating the weighted normalized matrix

The weighted normalized matrix (v_{ij}) is obtained multiplying the weight of each criteria by the normalized performance value of each cell and is given as:

$$v_{ij} = w_i r_{ij} \quad ; \quad i = 1, 2, \cdots, m \; ; \; j = 1, 2, \cdots, n \quad (28)$$

where w_i is the weight.

Step 4 – Determine Positive and Negative Ideal Solutions

For the positive ideal solutions (A^+):

$$A^+ = \begin{matrix} max(v_{ij}); \, if \, j \in B \\ min(v_{ij}); \, if \, j \in C \end{matrix} \quad (29)$$

$$A^+ = [v_1^+, \; v_2^+, \; \cdots, v_j^+] \quad (30)$$

For negative ideal solutions (A^-):

$$A^- = \begin{matrix} min(v_{ij}); \, if \, j \in B \\ max(v_{ij}); \, if \, j \in C \end{matrix} \quad (31)$$

$$A^- = [v_1^-, \; v_2^-, \; \cdots, v_j^-] \quad (32)$$

where B represent a benefit attribute; and C represents a cost attribute

Step 5 – Calculate the separation measure

Table 1. TOPSIS initial table of alternatives and criteria.

Weights Criteria Alternatives	w_1 C_1	w_2 C_1	$\cdots$ $\cdots$	w_n C_n
A_1	x_{11}	x_{12}	$\cdots$	x_{1n}
A_2	x_{21}	x_{22}	$\cdots$	x_{2n}
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
A_m	x_{m1}	x_{m2}	$\cdots$	x_{mn}

Here the separation matrix is obtained by finding the Euclidean distance from the ideal solutions and can be calculated by:

$$S_{iP}{}^{+} = \sqrt{\sum_{j}^{n} (v_{ij} - v_j^{+})^2} \quad ; \quad i = 1, 2, \cdots, m \tag{33}$$

$$S_{iN}{}^{-} = \sqrt{\sum_{j}^{n} (v_{ij} - v_j^{-})^2} \quad ; \quad i = 1, 2, \cdots, m \tag{34}$$

where $S_{iP}{}^{+}$ and $S_{iN}{}^{-}$ represents the Euclidean distances from the target alternative $'i'$ to the positive and negative ideal solutions respectively.

Step 6 – Relative closeness

The relative closeness to the ideal solution of the respective alternatives can be determined by:

$$R_i = \frac{S_{iP}{}^{+}}{S_{iP}{}^{+} + S_{iN}{}^{-}} \quad ; \quad 1 \leq i \leq m \tag{35}$$

where R_i is the relative closeness or the overall preference score for each alternative

Step 7 – Ranking of alternatives

This is the final step where the best alternatives are ranked in descending order of relative closeness(R_i).

2.2.2 Weight determination for multi-attribute problems

In multi-attribute decision making problems weights are required to convert the normalized matrix into a weighted normalized matrix as presented in §2.2.1 (step 3). A method of obtaining the weights to be used for the criteria weight calculations is based on the Analytic Hierarchical Process (AHP) with the procedure presented as follows (Balasundareshwaran et al. 2019; Saaty 1987).

Step 1 – Develop the pairwise comparison matrix

Using the Saaty's Pairwise comparison scale for Analytic Hierarchical Process (AHP) preferences shown in Table 2, populate the pair-wise comparison matrix based on the assigned relative importance a_i and a_j which will be represented as a_{ij} for every level of the respective criteria-($C_1, C_2, \cdots, C_n$). The pair-wise comparison matrix($A_{(n\times n)}$)is given as:

$$A_{(n\times n)} = (a_{ij}) = \begin{pmatrix} 1 & a_{12}\ldots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & a_{n2}\ldots & 1 \end{pmatrix} \quad with \;\; a_{ij}a_{ji} = 1 \;\; ; \;\; a_{ij} > 0 \tag{36}$$

Table 2. Scale of relative importance.

Level of importance	Definition
1	Equal importance
2	Equal to Moderate importance
3	Moderate importance
4	Moderate to Strong importance
5	Strong importance
6	Strong to Very Strong importance
7	Very Strong importance
8	Very Strong to Extreme importance
9	Extreme importance

Source: Saaty (1987).

i.e.

$$a_{ij} = \frac{1}{a_{ji}} \tag{37}$$

$$\therefore when\ i = j \quad ;\ a_{ij} = 1 \tag{38}$$

Step 2 – Generate normalized pairwise comparison matrix
The matrix is normalized by dividing the respective value in each cell by their respective column total, and can be obtained using Equation(42):

$$\ddot{a}_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \quad ; \quad i,\ j = 1, 2, 3 \ldots n \tag{39}$$

where a_{ij} and $\ddot{a}_{ij}$ represents the respective cell value(s) before and after normalization, respectively
Step 3 – Determine criteria weight
The weights(w_i) are thus calculated using Equation (43) which is given as:

$$w_i = \left(\frac{1}{n}\right) \sum_{i=1}^{n} \ddot{a}_{ij} \tag{40}$$

2.2.2.1 Consistency check in analytical hierarchy process.

Step 1 – Obtain weighted sum
Using the pairwise comparison matrix without normalization, the weighted sum value is calculated by:

$$w_{SV} = \sum_{i=1}^{n} w_j a_{ij} \tag{41}$$

where w_{SV} is the weighted sum value; w_j represent the criteria weight per column; and a_{ij} is the respective cell value before normalization.
Step 2 – Calculate the eigenvalue of the pairwise comparison matrix which is obtain by:

$$\lambda_i = \frac{w_{SV_i}}{w_i} \tag{42}$$

where λ_i is the eigenvalue of the pairwise matrix of the i-th term
Step 3 – Determine the maximum eigenvalue of the pairwise comparison matrix(λ_{max}) which is computed by:

$$\lambda_{max} = \left(\frac{1}{n}\right) \sum_{i=1}^{n} \lambda_i \tag{43}$$

Step 4 – Check consistency index (CI)
This entails determining the level of inconsistency in the pairwise comparison matrix (A) which is basically the normalized difference between the maximum eigenvalue and the size of the matrix which is obtained by:

$$CI = \frac{(\lambda_{max} - n)}{n - 1} \tag{44}$$

where n is the number of criteria.
Step 5 – Determine consistency ratio (CR)
This is obtained by comparing the consistency index (CI) with an average random consistency index (RI), which is given by:

$$CR = \frac{CI}{RI} \tag{45}$$

The average random consistency index (RI) is obtained from a sample of randomly generated matrices using the scale 1/9, 1/9, ..., 1, ..., 8, 9 and is presented in Table 3.

Step 6 – Interpretation

$$if\ CR \leq 0.1; \quad weights\ are\ accepted$$

$$if\ CR > 0.1; \quad re - evaluate\ the\ pairwise\ comparison$$

2.3 Input data

This section present the relevant data that served as input for the respective analysis carried out in this work and are presented in Tables 4 and 5, respectively.

3. Results and discussion

This section presents the results obtained from the comprehensive analysis of low/zero carbon technology diffusion and mapping, derived from the application of Bass and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) models used for technology diffusion and multi-criteria analysis, respectively. The mathematical formulations employed to produce these results were coded and computed using Engineering Equation Solver (EES) and the Microsoft Excel Integrated Environment. The outcomes are accompanied by relevant discussions to provide a comprehensive understanding of the findings; and through a meticulous examination of the results and their implications, we aim to shed light on the diffusion patterns, characteristics, and ranking of selected low/zero carbon technologies in the context of Nigeria's decarbonization objectives.

3.1 Results of technology diffusion analysis

In this subsection, the outcomes of a technology diffusion analysis conducted are presented. The analysis employs the Bass Model, and covers results of estimated Bass parameters, cumulative adoptions, time to peak adoptions, and adopter categories. The results shed light on the adoption patterns and characteristics of the low carbon technologies under investigation.

Table 3. Random consistency index (RI) (standard values).

N	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Source: Saaty (1987).

Table 4. Pertinent assumptions for market potential.

Item	Symbol	Unit	Value	Source
Nigeria Population	m_{pop}	People	221,176,130	Worldometers (2023)
Number of power plant (with verifiable output)	m_{PP}	Power plants	28	OpenInfraMap (n.d)
Number of hours in a year	t	hr	8760	
Nigeria current installed capacity	C_{inst}	MW	13,427	CSL Stockbrokers (2023)
Nigeria average CO_2Emission level (2023 forecast)	m_{CO_2}	$MtCO2eq/yr$	426.76	Ritchie and Roser (2023)
Global average energy demand per capita	$AEd_{pc,G}$	kWh	3576	Global Change Data Lab (2023)
Start year for adoption	-	yr	2023	

Table 5. Input data for least square regression analysis.

Energy generation technologies						
S/No	Technology	Unit	Year	Installed Capacity		Source
				Nigeria Data	Global Data	
1	Wind	MW	2013	NA	300,027.00	International Renewable Energy Agency (2023a)
			2014	NA	349,466.00	
			2015	NA	416,347.00	
			2016	NA	467,028.00	
			2017	NA	514,423.00	
			2018	NA	564,513.00	
			2019	NA	620,841.00	
			2020	NA	731,656.00	
			2021	NA	824,171.00	
			2022	NA	898,824.00	
				Installed Capacity		
2	Solar Photovoltaic	MW	2013	15	140514	International Renewable Energy Agency (2023a)
			2014	16	180712	
			2015	17	228920	
			2016	18	301082	
			2017	19	395947	
			2018	19	489306	
			2019	28	592245	
			2020	28	720429	
			2021	33	861537	
			2022	37	1053115	
				Installed Capacity		
3	Concentrating Solar Power	MW	2013	NA	3942	International Renewable Energy Agency (2023a)
			2014	NA	4599	
			2015	NA	4850	
			2016	NA	4970	
			2017	NA	5069	
			2018	NA	5811	
			2019	NA	6377	
			2020	NA	6511	
			2021	NA	6375	
			2022	NA	6501	
				Installed Capacity		
4	Hydropower	MW	2013	2110	1137292	International Renewable Energy Agency (2023a)
			2014	2110	1175663	
			2015	2111	1210331	
			2016	2111	1245935	
			2017	2111	1270950	
			2018	2111	1293744	
			2019	2111	1312084	
			2020	2111	1334078	
			2021	2111	1362715	
			2022	2111	1392598	
				Installed Capacity		
5	Bioenergy	MW	2013	8	84879	International Renewable Energy Agency (2023a)
			2014	9	90745	
			2015	9	96484	
			2016	10	105424	
			2017	10	111006	
			2018	10	118194	
			2019	10	124199	

(*Continued*)

Table 5. Continued.

Energy generation technologies						
S/No	Technology	Unit	Year	Installed Capacity		Source
				Nigeria Data	Global Data	
			2020	10	133236	
			2021	10	141302	
			2022	10	148912	
				Installed Capacity		
6	Geothermal	MW	2013	NA	10983	International Renewable Energy Agency (2023a)
			2014	NA	11424	
			2015	NA	12085	
			2016	NA	12405	
			2017	NA	13025	
			2018	NA	13471	
			2019	NA	14089	
			2020	NA	14417	
			2021	NA	14696	
			2022	NA	14877	
				Installed Capacity		
7	Nuclear	MW	2012	NA	361.07	International Atomic Energy Agency (2023)
			2013	NA	362.18	
			2014	NA	361.42	
			2015	NA	371.22	
			2016	NA	377.09	
			2017	NA	378.61	
			2018	NA	385.59	
			2019	NA	386.85	
			2020	NA	382.33	
			2021	NA	382.82	
				Hydrogen Demand		
8	Hydrogen	MW	2019	NA	91.2	International Energy Agency (2023d)
			2020	NA	89.5	
			2021	NA	94.3	
			2022f	NA	94.7	
			2023f	NA	98.1	
			2024f	NA	99.5	
			2025f	NA	102.2	
			2026f	NA	104.1	
			2027f	NA	106.5	
			2028f	NA	108.5	
			2029f	NA	110.9	
			2030f	NA	113.0	
				Installed Capacity		
9	Fuel cell	MW	2007	NA	70	Weidner, Ortiz-Cebolla, and Davies (2019)
			2008	NA	98	
			2009	NA	160	
			2010	NA	230	
			2011	NA	270	
			2012	NA	320	
			2013	NA	420	
			2014	NA	550	
			2015	NA	640	
			2016	NA	730	
			2017	NA	850	

(*Continued*)

Table 5. Continued.

Energy generation technologies						
S/No	Technology	Unit	Year	Installed Capacity		Source
				Nigeria Data	Global Data	
				Total Production		
10	Natural Gas	Bcm	2012	41	3430	Enerdata (2023)
			2013	37	3491	
			2014	42	3533	
			2015	44	3571	
			2016	42	3626	
			2017	45	3773	
			2018	46	3974	
			2019	46	4118	
			2020	46	4015	
			2021	45	4176	
Carbon capture and removal technologies						
				CCUS Capacity		
10	Carbon Capture Utilization and Sequestration (CCUS)	$MtCO_2$/Yr	2020	NA	41	International Energy Agency (2023e)
			2021	NA	42	
			2022	NA	44	
			2023f	NA	48	
			2024f	NA	73	
			2025f	NA	148	
			2026f	NA	184	
			2027f	NA	212	
			2028f	NA	226	
			2029f	NA	227	
			2030f	NA	265	
				DAC Operating Capacity		
11	Direct Air Capture (DAC) / Soda-Lime	tCO_2/yr	2020	NA	0	International Energy Agency (2023f)
			2021	NA	0	
			2022	NA	0.2	
			2023f	NA	0.3	
			2024f	NA	0.3	
			2025f	NA	9.8	
			2026f	NA	18.8	
			2027f	NA	25	
			2028f	NA	31.3	
			2029f	NA	38	
			2030f	NA	44.2	

^{*f} – forcasted data.

3.1.1 Results of estimated bass parameters

For both Nigeria-specific and global average data, Table 6 give the estimated regression coefficients and derived Bass parameters based on input data presented in Table 5. The evaluation of market potential (m) took into account factors such as the population size(m_{pop}) and energy demand(m_{ED}) for the energy technologies; as well as the number of power plants(m_{PP}) and Nigeria's carbon emission potential(m_{CO_2}) for the carbon mitigation technologies (See Table 4).

3.1.2 Results of cumulative adoptions

Cumulative adoption is a key idea in the Bass model and offers important insights on the acceptance and spread of new products or technologies. It helps to forecast market penetration, evaluate market potential, and develop a deeper comprehension of the dynamics of adoption through time which is crucial for making informed decisions and implementing effective strategies to encourage and expedite the adoption process. Understanding cumulative adoption is of utmost importance in successfully introducing and disseminating innovations across diverse markets and industries. Table 7

Table 6. Estimated Bass parameters based on Nigeria and global-average data for i-th technology.

S/No	Technology	Location	Estimated regression coefficients				Bass parameters wrt population (m_{pop})		Bass parameters wrt to energy demand (m_{ED})	
			a	***b***	***c***	R^2	***p***	***q***	***p***	***q***
Energy generation technologies										
1	Wind	Nigeria	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
		Global	276034.4916	0.118035127	−1.32505E-09	0.99	0.001245	0.1193	0.003049	0.1211
2	Solar Photovoltaic	Nigeria	13.69844562	0.055288011	0.000214945	0.96	6.177E-08	0.05529	1.513E-07	0.05529
		Global	113772.9214	0.223227863	−7.24456E-09	0.99	0.000513	0.2237	0.001257	0.2245
3	Concentrating Solar Power(CSP)	Nigeria	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
		Global	3611.768145	0.097736349	−7.9566E-07	0.95	0.00001629	0.09775	0.0000399	0.09778
4	Hydro	Nigeria	2109.60025	0.000203837	−6.8009E-09	0.78	0.000009513	0.0002133	0.0000233	0.0002271
		Global	1110454.471	0.029689007	−6.40735E-10	0.99	0.005007	0.0347	0.01227	0.04916
5	Bioenergy	Nigeria	7.680774997	0.072319092	−0.000521763	0.90	3.464E-08	0.07232	8.484E-08	0.07232
		Global	79141.43883	0.068310603	−6.80494E-09	0.99	0.0003569	0.06867	0.0008742	0.06918
6	Geothermal	Nigeria	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
		Global	10334.97288	0.053951454	−1.43183E-07	0.99	0.0000466	0.054	0.0001142	0.05407
7	Nuclear	Nigeria	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
		Global	350.6430462	0.01853585	−2.53114E-06	0.90	0.000001581	0.01854	0.000003873	0.01854
8	Hydrogen	Nigeria	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
		Global	87.77604979	0.021187583	−1.51739E-07	0.98	3.958E-07	0.02119	0.000001067	0.02119
9	Fuel Cell	Nigeria	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
		Global	64.87650753	0.260295661	−1.86905E-05	0.99	2.926E-07	0.2603	7.167E-07	0.2603
10	Natural Gas	Nigeria	37.14143581	0.043473672	−5.48598E-05	0.72	1.675E-07	0.04347	4.103E-07	0.04347
		Global	3324.024458	0.019237687	9.94821E-08	0.94	0.00001499	0.01925	0.00003672	0.01927
r Carbon capture and removal technologies										
S/No	Technology	Location	Estimated regression coefficients				Bass parameters w.r.t no. of power plants (m_{PP})		Bass parameters w.r.t to CO_2 emission (m_{CO2})	
		a	***b***	***c***	R^2	***p***	***q***	***p***	***q***	
11	Carbon Capture Utilization and Sequestration (CCUS)	Nigeria	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
		Global	11.82127264	0.340011599	−0.000120124	0.97	0.05784	0.3979	0.0277	0.3677
12	Direct Air Capture (DAC) and Lime-Soda	Nigeria	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
		Global	1.110975498	0.509995929	−0.001563724	0.98	0.005436	0.5154	0.002603	0.5126

Table 7. Cumulative adoption of technologies.

S/No	Technology	Time (years)	Energy generation technologies			
			Cumulative Adoptions			
			Global data with respect to		Nigeria data with respect to	
			Nigeria Population size	Nigeria Energy Demand (MW)	Nigeria Population Size	Nigeria Energy Demand (MW)
1	Wind	10	5,228,000	5,159	NA	NA
		20	21,020,000	19,220	NA	NA
		30	60,320,000	45,110	NA	NA
		40	124,100,000	70,470	NA	NA
		50	179,700,000	83,650	NA	NA
2	Solar Photovoltaic	10	4,190,000	4,117	182.9	0.18
		20	37,050,000	30,300	500.9	0.50
		30	145,500,000	75,070	1054	1.05
		40	210,100,000	88,620	2014	2.05
		50	220,500,000	90,320	3684	3.68
3	Concentrating Solar Power(CSP)	10	61,244	61.24	NA	NA
		20	223,885	223.69	NA	NA
		30	655,007	652.94	NA	NA
		40	1,793,000	1775	NA	NA
		50	4,762,000	4627	NA	NA
4	Hydro	10	12,840,000	12,680	21,118	21.12
		20	29,410,000	27,790	42,278	42.28
		30	49,710,000	43,490	63,482	63.48
		40	73,050,000	57,640	84,729	84.73
		50	98,020,000	68,860	106,019	106.02
5	Bioenergy	10	1,134,000	1,132	112.7	0.11
		20	3,361,000	3,330	344.9	0.34
		30	7,672,000	7,444	823.6	0.82
		40	15,780,000	14,660	1810	1.81
		50	30,240,000	25,960	3843	3.84
6	Geothermal	10	136,984	136.96	NA	NA
		20	371,394	371.44	NA	NA
		30	771,389	771.71	NA	NA
		40	1,450,000	1,452	NA	NA
		50	2,591,000	2,597	NA	NA
7	Nuclear	10	3852	3.85	NA	NA
		20	8489	8.49	NA	NA
		30	14071	14.07	NA	NA
		40	20788	20.78	NA	NA
		50	28874	28.87	NA	NA
8	Hydrogen	10	978	0.98	NA	NA
		20	2186	2.19	NA	NA
		30	3680	3.68	NA	NA
		40	5525	5.53	NA	NA
		50	7807	7.81	NA	NA
9	Fuel Cell	10	3116	3.11	NA	NA
		20	45191	45.17	NA	NA
		30	611787	609.36	NA	NA
		40	7,989,000	7,593	NA	NA
		50	74,380,000	50,050	NA	NA

(*Continued*)

Table 7. Continued.

S/No	Technology	Time (years)	Energy generation technologies – Cumulative Adoptions			
			Global data with respect to		Nigeria data with respect to	
			Nigeria Population size	Nigeria Energy Demand (MW)	Nigeria Population Size	Nigeria Energy Demand (MW)
10	Natural Gas	10	36,652	36.65	465	0.47
		20	81,077	81.07	1184	1.18
		30	134,917	134.89	2,294	2.29
		40	200,163	200.09	4,008	4.01
		50	279,222	279.06	6,656	6.66
			Carbon capture and removal technologies			
S/No	Technology	Time (years)	Cumulative Adoptions			
			Global data with respect to		Nigerian data with respect to	
			Nigeria Power plant	Nigeria CO_2 emission (*MtCO2eq*)	Nigeria Power plant	Nigeria CO_2 emission (*MtCO2eq*)
11	Carbon Capture Utilization and Sequestration (CCUS)	10	189	333.6	NA	NA
		20	204	424.5	NA	NA
		30	204	426.7	NA	NA
		40	204	426.8	NA	NA
		50	204	426.8	NA	NA
	Direct Air Capture (DAC) and Lime-Soda	10	134	198.3	NA	NA
12		20	204	423.9	NA	NA
		30	204	426.7	NA	NA
		40	204	426.8	NA	NA
		50	204	426.8	NA	NA

presents the cumulative number of adoptions for the energy-generating and carbon capture and removal technologies from 2023 till ten (10) to fifty (50) years into the future based on both global and Nigeria-specific diffusion rates.

3.1.3 Results of time to peak adoption

The time to peak adoption is another important measure that offers important insights into the timing and intensity of the diffusion process Understanding the mechanics of the time to peak adoption of a technology influences decisions with regard to resource allocation, competitive positioning, and market timing. Table 8 presents the calculated time to peak adoption for the selected low-carbon technologies, offering crucial information for strategic decision-making.

3.1.4 Results of adopter categories

This subsection presents the categories of adopters/adoption, q/p value, and the corresponding time duration for the respective technologies. A higher q/p value indicates that the adoption of a technology is significantly influenced by social factors, such as social influence or imitation. In other words, consumers are more likely to accept and adopt a new product or technology based on the suggestions or experiences of others, rather than being solely influenced by marketing initiatives. This underscores the importance of social ties, suggestions, and word-of-mouth in the adoption process. Conversely, for technologies with a lower q/p value, the coefficient of innovation (p) has a stronger impact on adoption than imitation(q) which means consumers' responses to the

Table 8. Estimated time to peak adoptions of low carbon technologies.

Energy generation technologies						
S/No	Technology	Unit	Time to Peak Adoptions			
			Global data with respect to		Nigeria data with respect to	
			Nigeria Population size	Nigeria Energy Demand	Nigeria Population Size	Nigeria Energy Demand
1	Wind	Years	37.86	29.66	NA	NA
2	Solar Photovoltaic	Years	27.1	22.97	247.9	231.7
3	Concentrating Solar Power(CSP)	Years	88.98	79.78	NA	NA
4	Hydro	Years	48.75	22.68	13,956	9092
5	Bioenergy	Years	76.2	62.39	201.2	188.8
6	Geothermal	Years	130.50	113.70	NA	NA
7	Nuclear	Years	505.4	457	NA	NA
8	Hydrogen	Years	513.9	467	NA	NA
9	Fuel Cell	Years	52.63	49.19	NA	NA
10	Natural Gas	Years	371.5	324.3	286.8	266.2
Carbon capture and removal technologies						
S/No	Technology	Unit	Time to Peak Adoptions			
			Global data with respect to		Nigerian data with respect to	
			Nigeria Power plant	Nigeria CO_2 emission	Nigeria Power plant	Nigeria CO_2 emission
11	Carbon Capture Utilization and Sequestration (CCUS)	Years	4.2	6.54	NA	NA
12	Direct Air Capture (DAC) and Lime-Soda	Years	8.7	10.25	NA	NA

technology adoption are more influenced by external factors like advertising campaigns, promotions, or product attributes, rather than the adoption behaviors of others.

Tables 9 and 10 present the q/p value, time duration, and the size of adopter categories for selected low carbon technologies. These tables incorporate global and Nigeria-specific data, considering market potential in terms of population size and energy demand for energy generating technologies, as well as the number of potential power plants and Nigeria's CO_2 emission levels for carbon capture and removal technologies.

3.2 Results of multi-criteria analysis

It is essential to assess the best technology options that fit Nigeria's energy mix after examining the pace of technological diffusion of each option in relation to the country's population and energy needs. This ranking takes into account a number of factors, including technology readiness, technical, economic, environmental, social, terrain-specific and /or due to primary energy resource potential. This was accomplished through the use of a multi-criteria analysis tool – Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and the outcomes are presented in this section. Cost (C), Time to Peak Adoption of Technology (TPA), Mitigation Potential (MP), and Technology Readiness Level (TRL) are the four parameters that were taken into consideration for the analysis. The coding for TRL is: '1' represents laboratory research level (TRL 1–3); '2' represents technology development plus small-scale demonstration (TRL 4–6); and '3' represents large-scale operational demonstration and commercialization (TRL 7–9). The results of the multi-criteria analysis are shown in Tables 11–17.

3.2.1 Weight determination via analytic hierarchy process

The Analytical Hierarchy Process (AHP) is a commonly employed method for determining weights in multi-criteria analysis. It offers a structured framework that allows decision-makers to evaluate the relative importance of criteria through pairwise comparisons. In this study, the AHP method is

Table 9. Estimated duration and size of the low-carbon technology adopter category based on global and Nigeria data with market potential based on Nigeria population and projected number of power plants.

Technology			Adopter Category								
			Innovators	Early Adopters		Early Majority		Late Majority		Laggards	
		q/p	% adopters	Years	% adopters	Years	% adopters	Years	% adopters	Beyond T_2years	% adopters
Energy generation technologies (market potential based on Nigeria population)											
Wind	Nigeria	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Global	95.83	0.12	26.93	20.18	10.93	29.17	10.93	29.17	48.78	21.35
Solar Photovoltaic	Nigeria	895047	0.05	224.10	21.13	23.82	28.87	23.82	28.87	271.70	21.13
	Global	436.1	0.05	21.23	20.90	5.87	28.93	5.87	28.93	33.98	21.18
Concentrating Solar Power (CSP)	Nigeria	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Global	6002	0.002	75.51	21.12	13.47	28.87	13.47	28.87	102.5	21.14
Hydro	Nigeria	22.43	0.0009	8047	17.61	5909	30.15	5909	30.15	19865	22.07
	Global	6.93	0.50	15.58	9.24	33.17	33.03	33.17	33.03	81.92	24.18
Bioenergy	Nigeria	2.08E + 06	0.000003	183.00	21.13	18.21	28.87	18.21	28.87	219.4	21.13
	Global	192.4	0.035	57.12	20.69	19.08	29.02	19.08	29.02	95.28	21.24
Geothermal	Nigeria	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Global	1159	0.004	106.2	21.06	24.37	28.89	24.37	28.89	154.9	21.15
Nuclear	Nigeria	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Global	11724	0.0002	434.40	21.13	71.04	28.87	71.04	28.87	576.40	21.13
Hydrogen	Nigeria	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Global	53530	0.00004	451.70	21.13	62.15	28.87	62.15	28.87	576.00	21.13
Fuel Cell	Nigeria	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Global	889745	0.00003	47.57	21.13	5.05	28.87	5.05	28.87	57.69	21.13
Natural Gas	Nigeria	259570	0.00001	256.50	21.07	30.29	28.87	30.29	28.87	317.1	21.13
	Global	1284	0.001	303.2	21.13	68.35	28.89	68.35	28.9	439.90	21.15
Carbon capture and removal technologies (market potential based on projected number of power plants)											
Carbon Capture Utilization and Sequestration (CCUS)	Nigeria	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Global	6.87	5.78	1.34	3.88	2.89	33.06	2.89	33.06	7.12	24.20
Direct Air Capture (DAC) and Lime-Soda	Nigeria	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Global	94.81	0.54	6.21	19.76	2.89	33.06	2.89	33.06	11.27	21.36

Table 10. Estimated duration and size of the low-carbon technology adopter category based on Nigeria and global data with market potential based on Nigeria energy demand and estimated CO_2 emission levels.

S/No	Technology			Adopter Category								
				Innovators	Early Adopters		Early Majority		Late Majority		Laggards	
			q/p	% adopters	Years	% adopters	Years	% adopters	Years	% adopters	Beyond T_2years	% adopters
Energy generation technologies (market potential based on Nigeria energy demand)												
1	Wind	Nigeria	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
		Global	39.71	0.30	19.05	18.84	10.61	29.59	10.61	29.59	40.27	21.66
2	Solar Photovoltaic	Nigeria	365376	0.00001	207.9	21.13	23.82	28.87	23.82	28.87	255.5	21.13
		Global	178.60	0.13	17.14	20.57	5.83	29.03	5.83	29.03	28.80	21.25
3	Concentrating Solar Power(CSP)	Nigeria	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
		Global	2451	0.004	66.32	21.10	13.46	28.88	13.46	28.88	93.25	21.14
4	Hydro	Nigeria	9.74	0.002	3833	13.04	5258	31.83	5258	31.83	14350	23.30
		Global	3.42	1.22	1.60	3.15	24.29	37.31	24.29	37.31	46.97	27.31
5	Bioenergy	Nigeria	852369	0.000009	170.6	21.13	18.21	28.87	18.21	28.87	207	21.13
		Global	79.14	0.09	43.60	20.05	18.80	29.23	18.80	29.23	81.19	21.40
6	Geothermal	Nigeria	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
		Global	473.6	0.011	89.39	20.95	24.31	28.93	24.31	28.93	138	21.18
7	Nuclear	Nigeria	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
		Global	4786	0.0003	385.90	21.12	71.02	28.87	71.02	28.87	528	21.14
8	Hydrogen	Nigeria	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
		Global	19860	0.0001	404.90	21.13	62.15	28.87	62.15	28.87	529.2	21.13
9	Fuel Cell	Nigeria	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
		Global	363212	0.00007	44.13	21.13	5.05	28.87	5.05	28.87	54.24	21.13
10	Natural Gas	Nigeria	105962	0.00004	235.90	21.13	30.29	28.87	30.29	28.87	296.4	21.13
		Global	524.9	0.003	256.10	20.98	68.20	28.92	68.20	28.92	392.50	21.17
Carbon capture and removal technologies (market potential based on Nigeria estimated CO_2 emission levels)												
11	Carbon Capture Utilization and Sequestration (CCUS)	Nigeria	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
		Global	13.27	2.77	3.20	12.42	3.33	31.04	3.33	31.04	9.87	22.72
12	Direct Air Capture (DAC) and Lime-Soda	Nigeria	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
		Global	196.9	0.26	7.69	20.47	2.55	29.01	2.55	29.01	12.81	21.24

Table 11. Decision making matrix.

S/No	Technology	Non-benefit		Benefit	
		Criteria-1 C ($US\$/kW$)	Criteria-2 TPA(yr)	Criteria-3 MP($MtCO2/yr$)	Criteria-4 TRL
1	Wind	2858[a]	29.66	232.5[f]	3
2	Solar PV	857[a]	22.97	232.5[f]	3
3	CSP	4746[a]	79.78	134.7	2
4	Hydro	2135[a]	22.68	3000[h]	3
5	Bioenergy	2353[a]	62.39	2[m]	2
6	Geothermal	3991[a]	113.7	50[n]	3
7	Nuclear	9000[o]	457	1100[e]	3
8	Hydrogen	1583[c]	467	2857[d]	1
9	Fuel cell	3140[i]	49.19	3000[n]	2
10	Natural gas	1155[p]	324.3	27.77[g]	3
		C ($US\$/tCO_2$)			
11	CCUS	120[b]	6.54	48[L]	2
12	DAC/SL	342[k]	10.25	0.3[j]	2

Source(s): [a]International Renewable Energy Agency (2023b); [b]Baylin-Stern and Berghoit (2023); [c]International Energy Agency (2023g); [d]International Energy Agency (2023h); [e]International Energy Agency (2023i); [f]International Energy Agency (2022); [g]International Energy Agency (2023j); [h]International Energy Agency (2023k); [i]Battelle Memorial Institute (2016); [j]International Energy Agency (2023f); [k]International Energy Agency (2023l); [L]International Energy Agency (n.d.); [m]International Energy Agency (2023m); [n]Napp et al. (2017); [o]World Nuclear Association (2023); [p]PennState (2023).

Table 12. Vector normalization.

S/No	Technology	Non-benefit		Benefit	
		Criteria-1 C	Criteria-2 TPA	Criteria-3 MP	Criteria-4 TRL
1	Wind	0.231600491	0.039643	0.044333	0.34641
2	Solar PV	0.069447733	0.030701	0.044333	0.34641
3	CSP	0.384596197	0.106631	0.025684	0.23094
4	Hydro	0.173011563	0.030313	0.572033	0.34641
5	Bioenergy	0.190677381	0.083388	0.000381	0.23094
6	Geothermal	0.323414122	0.151967	0.009534	0.34641
7	Nuclear	0.72932275	0.61081	0.209745	0.34641
8	Hydrogen	0.128279768	0.624176	0.544766	0.11547
9	Fuel cell	0.254452604	0.065746	0.572033	0.23094
10	Natural gas	0.09359642	0.433448	0.005295	0.34641
11	CCUS	0.009724303	0.008741	0.009153	0.23094
12	DAC/SL	0.027714264	0.0137	5.72E-05	0.23094

Table 13. Initial pairwise comparison matrix (fraction).

	C	TPA	MP	TRL
C	1	5	2	5
TPA	1/5	1	1/5	2
MP	1/2	5	1	4
TRL	1/5	1/2	1/4	1

Table 14. Check consistency.

Weights	C 0.48937	TPA 0.10421	MP 0.33028	TRL 0.07613	Weighted Sum	λ_i	λ_{Max}
C	1.00	5.00	2.00	5.00	2.051678	4.192498782	4.130412
TPA	0.20	1.00	0.20	2.00	0.420414	4.034126258	
MP	0.50	5.00	1.00	4.00	1.400577	4.240545612	
TRL	0.20	0.50	0.25	1.00	0.308686	4.054477145	

Table 15. Consistency index and ratio.

Consistency Index (CI) $(\lambda_{Max} - n)/(n - 1)$	Consistency ratio (CI/RI)
4.130412	0.048301

Table 16. Weighted normalized matrix.

S/No	Technology	Non-benefit		Benefit	
		Criteria-1 C	Criteria-2 TPA	Criteria-3 MP	Criteria-4 TRL
1	Wind	0.113338055	0.004131	0.014642	0.026374
2	Solar PV	0.033985554	0.003199	0.014642	0.026374
3	CSP	0.18820938	0.011112	0.008483	0.017583
4	Hydro	0.084666462	0.003159	0.188932	0.026374
5	Bioenergy	0.093311562	0.00869	0.000126	0.017583
6	Geothermal	0.158268781	0.015837	0.003149	0.026374
7	Nuclear	0.356907801	0.063655	0.069275	0.026374
8	Hydrogen	0.062776116	0.065048	0.179927	0.008791
9	Fuel cell	0.124521166	0.006852	0.188932	0.017583
10	Natural gas	0.045803168	0.045172	0.001749	0.026374
11	CCUS	0.004758771	0.000911	0.003023	0.017583
12	DAC/SL	0.013562496	0.001428	1.89E-05	0.017583

Table 17. Separation measures, relative closeness and rank.

S/No	Technology	Separation measure		Relative Closeness CCi	RANK
		Si Positive	Si Negative		
1	Wind	0.20537006	0.252111212	0.551085317	9
2	Solar PV	0.17673843	0.329586132	0.650938464	5
3	CSP	0.25767697	0.177530658	0.407921748	11
4	Hydro	0.07993931	0.337554484	0.808525754	1
5	Bioenergy	0.20887137	0.269697017	0.563549591	8
6	Geothermal	0.2414614	0.2054218	0.459676708	10
7	Nuclear	0.37717849	0.071466917	0.159294881	12
8	Hydrogen	0.08871209	0.344790102	0.795359527	2
9	Fuel cell	0.12023148	0.305214595	0.717399009	3
10	Natural gas	0.19667558	0.312239187	0.613539258	7
11	CCUS	0.18611716	0.358062597	0.657985885	4
12	DAC/SL	0.18932339	0.349300497	0.648505397	6

employed to determine the criteria weights, and subsequently verify consistency, as presented in Tables 13–15. The intermediate processes and results leading to the final criteria weights are outlined in Appendix A (refer to Tables A.1–A.3).

3.2.2 TOPSIS results after weighting and normalization

Having obtained the weights, the results of normalized weighted matrix, positive and negative ideal solutions, separation measures, relative closeness and rank were determined and are presented in Tables 16 and 17. However, for the results of the positive and negative ideal solutions, please refer to the Appendix (See Tables A.4 and A.5, respectively).

4. Critical findings and discussions

The findings arising from the results of technology diffusion and multi-criteria analysis conducted is presented in this section. The analysis of technology diffusion focused on adoption, considering Nigeria population and estimated required energy demand. However, for the purpose of discussion, the preference of this article is to highlight the technology diffusion characteristics mostly in relation to energy demand; and also draw conclusion and/or proffer recommendations based on the ranking of the multi-criteria analysis. By empirically assessing the diffusion and mapping of low/zero carbon technology diffusion and mapping for Nigeria's decarbonization, this article provides the following key findings and corresponding discussions.

- Several low/zero carbon technologies that offer significant mitigation potential have not found significant adoption in Nigeria. They include wind, concentrating solar plant (CSP), geothermal, nuclear, hydrogen, fuel cell for the energy generating technologies and for carbon capture and removal technology, they are carbon capture utilization and sequestration (CCUS), direct air capture (DAC) and lime soda technology.
- For energy generating technologies that are operational in Nigeria, such as hydro, natural gas, bioenergy, and solar photovoltaic, projections based on Nigeria estimated required energy demand with respect to Nigeria data for technology use shows that if the current trajectory of penetration in Nigeria is sustained in the next fifty (50) years, starting from year 2023 cumulative adoptions would amount to 21.12 MW, 0.47MW, 0.11MW and 0.18MW in the short term (circa year 2033); 63.48MW, 2.20MW, 0.82MW and 1.05MW in the medium term (circa year 2053); and 106.02MW, 6.66MW, 3.84MW, and 3.68MW in the long term (circa year 2073), respectively for the technologies which depicts a very slow adoption. Conversely, when applying the average global trajectory of technology use to Nigeria's estimated energy demand, the cumulative adoptions are projected to reach 12,680MW, 36.65MW, 1,132MW, and 4,117MW in the short term (circa year 2033); 43,490MW, 134.89MW, 7,444MW and 75,070MW in the medium term (circa 2053); and 68,860MW, 279.06MW, 25,960MW, and 90,320MW in the long term (circa year 2073), respectively, over the same fifty-year period. This shows that based on current Nigeria trajectory of use, the highest cumulative adoptions was from hydro, followed by natural gas, bioenergy and solar photovoltaic technology. While with respect to the average global trajectory of technology use the highest cumulative adoptions in fifty (50) years was seen to be from solar photovoltaic, followed by hydro, bioenergy, and natural gas.
- Furthermore, the findings suggest that for energy-generating technologies currently unavailable in Nigeria, such as wind, concentrating solar power (CSP), geothermal, nuclear, hydrogen, and fuel cell technologies, if Nigeria were to intensify efforts to adopt any of these technologies based on the average global trajectory of technology use in relation to Nigeria's estimated energy demand, the potential electricity generation for Nigeria from these technologies would be 5,159MW, 61.24MW, 136.96MW, 3.85MW, 0.98MW, and 3.11MW in the short term (circa year 2033); 45,110MW, 652.94MW, 771.71MW, 14.07MW, 3.68MW, and 609.36MW in the medium term (circa year 2053); and 83,650MW, 4,627MW, 2,597MW, 28.87MW, 7.81MW, and 50,050MW in the long term (circa year 2073), respectively, for the highlighted technologies.
- Overall for all the highlighted energy generating technologies based on average global trajectory of technology use with respect to cumulative adoptions by the Nigeria population, results show that in the next fifty (50) years, solar photovoltaics, wind, hydro, fuel cell and bioenergy technologies are the first five (5) most promising technologies..
- The time to peak adoption for existing technologies represented in Nigeria, based on Nigeria-specific data on technology usage in relation to Nigeria's energy demand was too far off into the future with bioenergy (188.8 years) exhibiting the fastest time to adoption, followed by natural gas (266.2 years), solar photovoltaic (231.7 years), and hydro (9092 years) technologies. As for all the highlighted technologies, including those not currently utilized in Nigeria, and based on the average global trajectory of technology use, hydro (22.68 years) demonstrates the fastest time to adoption among the energy generating technologies, followed by solar photovoltaic (22.97 years), wind (29.66 years), fuel cell (49.19 years), bioenergy (62.39 years), concentrating solar power (79.78 years), geothermal (113.70 years), natural gas (324.3 years), nuclear (457 years), and hydrogen (467 years) technologies. Regarding carbon capture and removal technologies,

carbon capture utilization and sequestration (CCUS) (4.2 years) exhibit the fastest time to adoption, followed by direct air capture and lime-soda (8.7 years) technologies.
- The outcomes of the multi-criteria analysis utilizing the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) generated a ranking of the most promising low/zero carbon technology options. This ranking took into account factors such as Cost (C), Time to Peak Adoption of Technology (TPA), Mitigation Potential (MP), and Technology Readiness Level (TRL). Based on this analysis, it can be inferred that adoption efforts for Nigeria could be intensified for already matured technology options such as hydro, solar photovoltaic, natural gas, bioenergy, wind, and concentrating solar power. Conversely, for technologies that may be considered novel, not fully matured, or influenced by specific resource constraints in Nigeria, exploratory investigations into options like hydrogen, fuel cell, geothermal, and nuclear can help elucidate the benefits of introducing them to Nigeria's energy mix.

5. Conclusion

An analysis to provide valuable insights into the diffusion and mapping of low/zero carbon technologies for Nigeria's decarbonization has been presented in this article. Through technology diffusion analysis and multi-criteria analysis, critical findings emerged. Firstly, it is evident that there is a significant potential for mitigation through the adoption of low/zero carbon technologies in Nigeria. However, it is concerning that certain technologies with substantial mitigation potential, such as wind, concentrating solar power, geothermal, nuclear, hydrogen, and carbon capture utilization and sequestration (CCUS), are currently not represented in Nigeria. Furthermore, the projections based on Nigeria's estimated energy demand highlight the slow adoption rate of the technologies currently utilized in the country. If the current trajectory persists, cumulative adoptions in the next fifty years will be relatively low. Comparatively, applying the average global trajectory of technology use to Nigeria's estimated energy demand reveals a more substantial potential for cumulative adoptions. Hydro, natural gas, bioenergy, and solar photovoltaic technologies have shown the highest cumulative adoptions based on Nigeria's current trajectory. However, when considering the average global trajectory, solar photovoltaic technology emerges as the leading option, followed by hydro, bioenergy, and natural gas. Finally, multi-criteria analysis, employing the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), has provided a ranking of the most promising low/zero carbon technology options. This ranking, considering factors such as cost, time to peak adoption, mitigation potential, and technology readiness level, suggests that efforts should focus on intensifying the adoption of already matured technologies such as hydro, solar photovoltaic, natural gas, bioenergy, wind, and concentrating solar power. However, it is also crucial to explore technologies like hydrogen, fuel cell, geothermal, and nuclear, taking into account their specific constraints and potential benefits within Nigeria's energy mix. It is noteworthy that enhancing the adoption of these technologies requires a focus on targeted policies, incentives, and infrastructure development. Continued research and monitoring of technology trends, along with adaptive policy frameworks, will be crucial for achieving sustained success in Nigeria's decarbonization journey.

The implications of the study's findings extend beyond the immediate context, holding significant relevance for other African and developing economies. One notable contribution lies in the identification of promising low-carbon technologies. The study's systematic ranking of these technologies based on their diffusion potential offers invaluable guidance to countries seeking to embark on their decarbonization journeys. This insight becomes a compass for decision-makers, aiding them in strategically prioritizing technologies for maximum impact. Furthermore, the study equips policymakers with a nuanced understanding of the factors influencing the adoption of low-carbon technologies. This depth of insight is instrumental in the development of effective adoption strategies. Armed with this knowledge, policymakers can design targeted interventions, surmounting barriers, and facilitating the swift integration of these technologies into existing infrastructures. Moreover, the study serves as a catalyst for capacity building in African and developing economies. The findings offer a foundation upon which to raise awareness and enhance understanding of the deployment and operation of low-carbon technologies. This, in turn, empowers local communities and institutions to actively engage in sustainable practices, fostering a collective commitment to a low-carbon future. In summary, the study's broad-ranging implications underscore its pivotal role in shaping the trajectory of environmentally conscious technological adoption across diverse economic landscapes.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The data that support the findings of this study are available. If further clarification, request or permission for use of specific materials is needed, please contact the corresponding author Chinedum Oscar Nwachukwu at nwachukwu.-chinedum@yahoo.com upon reasonable request.

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Appendix

Table A.1. Initial pairwise comparison matrix (decimals).

	C	TPA	MP	TRL
C	1.00	5.00	2.00	5.00
TPA	0.20	1.00	0.20	2.00
MP	0.50	5.00	1.00	4.00
TRL	0.20	0.50	0.25	1.00

Table A.2. Normalized pairwise comparison matrix.

	C	TPA	MP	TRL
C	0.526315789	0.434782609	0.57971	0.416667
TPA	0.105263158	0.086956522	0.057971	0.166667
MP	0.263157895	0.434782609	0.289855	0.333333
TRL	0.105263158	0.043478261	0.072464	0.083333

Table A.3. Criteria weights.

	C	TPA	MP	TRL	Weights
C	0.526315789	0.43478261	0.57971	0.416667	0.48937
TPA	0.105263158	0.08695652	0.057971	0.166667	0.10421
MP	0.263157895	0.43478261	0.289855	0.333333	0.33028
TRL	0.105263158	0.04347826	0.072464	0.083333	0.07613

Table A.4. Positive ideal solution.

S/No	Technology	Non-benefit		Benefit	
		Criteria-1 C	Criteria-2 TPA	Criteria-3 MP	Criteria-4 TRL
1	Wind	0.00475877	0.000911	0.188932	0.026374
2	Solar PV	0.00475877	0.000911	0.188932	0.026374
3	CSP	0.00475877	0.000911	0.188932	0.026374
4	Hydro	0.00475877	0.000911	0.188932	0.026374
5	Bioenergy	0.00475877	0.000911	0.188932	0.026374
6	Geothermal	0.00475877	0.000911	0.188932	0.026374
7	Nuclear	0.00475877	0.000911	0.188932	0.026374
8	Hydrogen	0.00475877	0.000911	0.188932	0.026374
9	Fuel cell	0.00475877	0.000911	0.188932	0.026374
10	Natural gas	0.00475877	0.000911	0.188932	0.026374
11	CCUS	0.00475877	0.000911	0.188932	0.026374
12	DAC/SL	0.00475877	0.000911	0.188932	0.026374

Table A.5. Negative ideal solution.

S/No	Technology	Non-benefit		Benefit	
		Criteria-1 C	Criteria-2 TPA	Criteria-3 MP	Criteria-4 TRL
1	Wind	0.3569078	0.065048	1.889E-05	0.0087913
2	Solar PV	0.3569078	0.065048	1.889E-05	0.0087913
3	CSP	0.3569078	0.065048	1.889E-05	0.0087913
4	Hydro	0.3569078	0.065048	1.889E-05	0.0087913
5	Bioenergy	0.3569078	0.065048	1.889E-05	0.0087913
6	Geothermal	0.3569078	0.065048	1.889E-05	0.0087913
7	Nuclear	0.3569078	0.065048	1.889E-05	0.0087913
8	Hydrogen	0.3569078	0.065048	1.889E-05	0.0087913
9	Fuel cell	0.3569078	0.065048	1.889E-05	0.0087913
10	Natural gas	0.3569078	0.065048	1.889E-05	0.0087913
11	CCUS	0.3569078	0.065048	1.889E-05	0.0087913
12	DAC/SL	0.3569078	0.065048	1.889E-05	0.0087913