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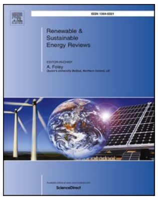

A review of Nigerian energy access studies: The story told so far

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ABSTRACT

Nigeria has been accorded the largest economy in Africa and one of Africa's burgeoning economies. However, a high percentage of the population lives in extreme poverty and is largely rural, accounting for about 51% of the total, approximately 96 million people in 2016. This glaring reality is most evident in the undisputed urban and rural divide with a huge mass of the population living in these rural areas characterised by underdevelopment and limited access to electricity and modern energy services. Energy access is an indispensable instrument such that can be used to achieve great strides in human development, better the economy and enable sustainable development. The present work reviews the state of the art on Nigerian energy access studies and provides an overview of the peer-reviewed literature spanning energy planning, electrification planning, rural electrification, renewable resource potential, energy & electricity access impact, and policies & reforms. It delineates the narrative in existing literature and propounds a new trajectory for future work. This study was facilitated by an extensive systematic literature review which has resulted in an analysis of 90 relevant articles out of a total of 104 articles from a period of 1978–2019. The review reveals no consensus on a standardized framework to synergize the already available strategies and methodologies for improving Nigeria's energy access. An integrated framework that embodies a multi-disciplinary study is introduced and forms the foundation upon which the authors of this paper are conducting further research to conceptualize a unified road map for energy planning, system design, and operation with renewable energy integration geared towards improving localized energy access in Nigeria.

1. Introduction

Nigeria is the seventh largest nation on earth and Africa's most populous nation [1] and thus offers a huge market opportunity having been established as the largest economy in Africa. Nigeria is not only a regional power, enumerated as one of the "Next Eleven" economies [2], it also belongs to the Commonwealth of Nations assembly, thus providing a strategic destination for investors and foreign direct investments (FDI) [3]. With its population growing at a rate of 2.6% per year, it is no fallacy that the Nigerian population is exploding. According to the United Nations, at this rate, Nigeria is set to become the third most populated country on the globe amassing a population of 480 million people by 2050 while having already reached the 200 million people landmark in 2019 [4]. While these statistics could have some positive impacts, some negative impacts are envisaged. For example, rising populations place the agricultural sector under severe and undue duress resulting in depletion of soil nutrients and heightening the likelihood of food insecurity and consequently famine [5] more especially considering the devastating effects of climate change [6,7]. More so, there are aggravated cases of increasingly unhealthy living conditions brought on by uncoordinated urbanization [8]. With regard to the positive impacts, the rising populations could massively contribute to the proliferation of a vibrant labor force, especially in the face of growing average life expectancy [9]. However, a large number of Nigerians live in penury and this is manifest in macro-economic indicators through her gross domestic product per capita (GDP per capita). Moreover, the largest contributors to the GDP (see Fig. 1) and the Nigerian economy have been known to seldom require large amounts of labour. As a result more than one million new annual entrants fail to be absorbed into the labor market thus resulting in very high rates of unemployment and underemployment of 43% as at the third quarter of 2018 [10]. A comparison of the Nigerian situation with other countries is made in Table 1 and this reflects Nigeria's position from a global perspective.

Furthermore, the World Poverty Clock report shows that Nigeria has surpassed India as the country in the globe where the poorest of the poor

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reside [12] and has earned the label of "the poverty capital of the world". As of June 2018, Nigeria was reported to have the highest number of people in extreme poverty with approximately 87 million Nigerian citizens living in extreme and abject poverty [12,13]. This has resulted in Nigeria been tagged with a sustainable development goal 1 (SDG1) status of "Poverty Rising" which does not bode well especially with the many challenges the country is facing including a major population boom [13]. According to the World Bank statistics [14], the rural population made up about 51% of the total in 2016 of which only 41% have access to electricity as compared to 86% of the urban population. More so, the importance of electricity is not overemphasized as it has been viewed as one very vital tool for enhancing human lives and living standards especially for people residing in rural areas. Energy access and electricity are critical elements instrumental for attaining sustainable development and can reinforce its main cornerstones. These include the economy by reinvigorating productivity; overall wellbeing by buttressing safety, security and enhancing standards of livelihood; and the environment by curbing overall pollution whilst remedying the degraded environment [15]. In addition, in order to combat issues such as poverty, lack of human welfare, economic stalemate or better yet regression, energy access can be seen as the proverbial "golden goose". Indeed, this clear-cut disparity between urban and rural areas is quite glaring globally [8], and this mirrors the situation apparent in Nigeria [16,17]. More so, the population in these rural areas is quite dispersed rendering it highly inaccessible and geographically siloed [9], the population also has a high level of illiteracy and their environment is severely underdeveloped in terms of basic infrastructures and social amenities [18].

The present study performs an extensive systematic literature review of the state of the art on Nigerian energy access studies and provide an overview of the narrative contained in this literature. This aims to provide the arsenal to enhance proper planning and strategizing for improving localized energy access. The paper has six main sections, Section 2 provides an overview of the Nigerian energy situation considering the history of the power sector, state of affairs in the energy situation and the rural electrification endeavors expended by the government; Section 3 describes the review methodology employed; Section 4 discusses details of the reviewed articles while Sections 5 and 6 provide the discussion and conclusions.

2. The Nigerian energy situation

2.1. A cursory tale of the Nigerian Power sector

The Government of the Federal Republic of Nigeria initially assumed the sole custody and completely oversaw the energy sector activities and, as a result, was tasked with its entire management. It was responsible for devising energy policies, plans, and regulations in addition to co-ordinating investment and operation actions. This was the state of affairs maintained up till 2005. The Federal Ministry of Power (FMP) acted on regulating the power sector activities whilst the custodian of operations was the National Electric Power Authority (NEPA) who singlehandedly spearheaded actions regarding the generation, transmission, and distribution of electricity. A monopolistic system of operation was in play from the very beginning of NEPA in 1972. It awarded the institution full authority over the functions of transmission and distribution in addition to full ownership of the marketing sector while maintaining a 94% rein of power generation related activities. This deemed very unproductive and unsustainable power system governance led to the dissolution of NEPA in 2005 [19]. Considering the importance of private sector involvement and equity, plans were set in motion to denationalize the Nigerian power sector. Actions aimed to invigorate private energy firms' participation and procurement of energy generation and distribution holdings so much so that a definite framework to reform the power sector was drawn up the same year with NEPA's cessation. However, the first proactive step was taken in 2010 when the Power Sector Reform roadmap was set in motion. NEPA was replaced by the Power Holding Company of Nigeria (PHCN). Dispelling the former monopolistic system, a single entity no longer managed the operation in terms of the generation, transmission, and distribution of electricity. Private stakeholders began to run the generation and distribution companies which consequently sprung up and assumed responsibility while transmission responsibility was bestowed upon the Transmission Company of Nigeria (TCN). In 2013, the government asserted full ownership of TCN but delegated its management to Manitoba Hydro International (MHI) [20]. The rationale behind this action by the government was to reorganize the modus operandi and deregulate the Nigerian power sector for improved performance. At the beginning of 2012, the government withdrew a substantial portion of fuel subsidy having already deregulated the fuel market in 2009. This deduction availed revenues that were supposedly redirected towards infrastructure investments [21].

As it stands, an overview of the major actors in the Nigerian Power sector as proffered from the Office of the Vice President include the

Table 1
Comparison of Nigeria with other countries with some Electricity and Economic indicators based on World Bank Development Indicators (2016).

Country	Electrification Access (%)	GDP (Billion US$)	GDP Per Capita (US$)	Electricity consumption (MWh/capita)
China	100	11,218	7993.07	4.05
United States	100	18,624	57,807.74	12.83
India	82	2260	1706.46	0.86
Italy	100	1859	31,279.07	5.1
Nigeria	61	405	2175.65	0.14
South Africa	86	295	5274.26	4.15

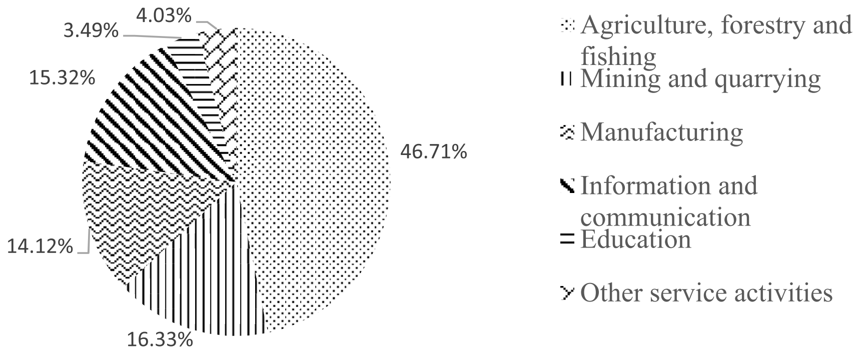

Fig. 1. Sectorial contribution to GDP (2017, Q3) [11].

Presidency, the national regulatory boards, some Federal ministries (power, finance and petroleum resources), national council bodies and public entities representatives. Concerning the daily operations of the power market, there are targeted participation involved from the Nigerian national oil company with some of its subsidiaries, the electricity trading sects, the national transmission company for handling operations, independent power plant owners for infrastructure development and players in the private sector space especially the indigenous generation and distribution companies [20].

2.2. The state of affairs on Nigeria's energy resources and consumption

Nigeria has been tremendously blessed with resources but has not reaped the benefits of these resources in its energy supply. Diverse energy resources abound in the country in very large amounts including conventional fossil and renewable energy resources. For conventional energy resources, Nigeria boasts of a vast wealth of oil, natural gas, lignite, and coal. Nigeria is among the largest oil-producing nations around the globe and the African nation with the largest natural gas reserve. For renewables, there abound a vast amount of resources from biomass, solar, hydropower to wind resources. Table 2 presents Nigeria's energy reserves and their potentials.

According to the International Energy Agency (IEA) statistics [24], in 2016 Nigeria's primary energy supply was 149.964 Mtoe excluding electricity trade. The historical development of the TPES is shown in Fig. 2. The observed rising trend was ascribed to the growth in the population and the economy. The largest energy contributor to the TPES was biofuels and waste materials, from which fuelwood or firewood emerged the most consumed energy source. The residential sector was the largest energy-consuming sector (see Fig. 4). The TPES consumption behavior was attributed to the high costs of refined petroleum products for household fuel requirements and the lack of domestic refining capabilities and gas distribution infrastructure.

In 2016, Nigeria also registered a low level of energy consumption at 129.6 Mtoe. This predicament brought on by incessant fuel scarcity and severe power outages has plagued the country during critical festive periods when there is high demand. Consequently, a large number of the citizens have resorted to auto power generation via petrol or diesel generator sets to provide their basic electricity needs [26]. Notwithstanding, the energy demand has continued to soar and Sambo et al. [27] have ascribed this phenomenon to increasing economic development and population growth.

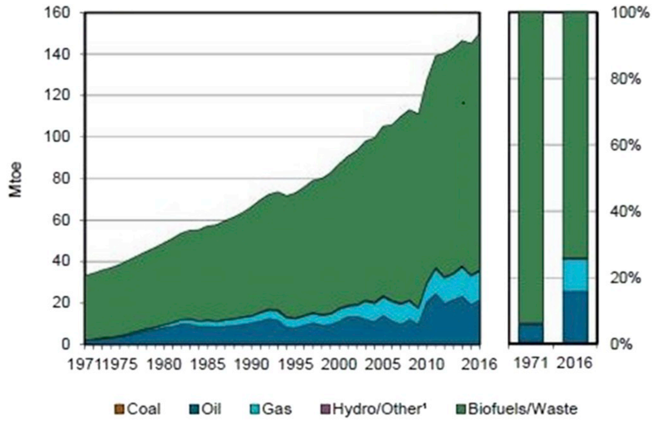

Fig. 2. Nigeria's total primary energy supply (TPES) (IEA, 2016) [24,25].

As at the third quarter of 2018, Nigeria had an installed power generation capacity of 13,435 MW of 28 grid-connected generating plants comprising thermal (Simple Cycle Gas Turbine (SCGT), Combined Cycle Gas Turbine (CCGT) and Gas Fired Steam Turbine) plants and hydropower plants (see Fig. 3). The available capacity was 8200 MW with a record high peak generation of 5,162 MW on the September 19, 2018 [28,29,31]. The total amount of energy received by the electricity distribution companies (DISCOs) was 6,376 GWh in the third quarter. However, just about 5,160 GWh was distributed (2389 MW equivalent to 20% of installed generation capacity). This performance level has persisted and even worsened in recent times. This has been attributed to the entire power system array been poorly or seldom maintained. The infrastructures have become antiquated such that there is a dire need to overhaul the entire system. The efforts exerted towards rehabilitating and maintaining existing systems have not yielded benefits for the nation's power supply. About 3,000 MW (from the beginning of 2015 to mid-2015) has been lost as a result of fuel shortages, frequency control issues, and other technical system problems. The state of the sector's finances is in a dire situation since the distribution companies are not generating enough revenue to offset their full market costs. According to the Nigerian Electricity Regulatory Commission (NERC) [28], DISCOs lost about 1.9 kWh of every 10 kWh of energy received from the

Table 2
Nigeria's energy reserves and their potentials ([21–23]).

Resource	Reserve	Energy Units (Btoe)	Production
	Natural Units		
Crude Oil	37,453 million bbl	5.24	1.83 million bbl/day in 2016
Natural Gas	193,354.99 billion scf	5.01	2777.79 billion SCF in 2016
Coal and Lignite	2.175 billion tonnes	–	–
Tar Sand	31 billion bbl of equivalent	–	–
Large Hydropower	11,250 MW	0.8 (over 40 years)	1938 MW
Small Hydropower	3500 MW	0.34 (over 40 years)	30 MW
Solar	3.5 kWh/m^2/day – 7.0 kWh/m^2/day (4.2million MWh/day using 0.1% land area)	5.2 (40 years and 0.1% land area)	6 MWh/day
Wind	2–4 m/s @ 10 m height mainland	0.0003 (4 m/s @ 12% probability, 70 m height, 20 m rotor, 0.1% land area, 40 years)	–
Municipal waste	18.5 million ton produced in 2005 estimated at 0.5kg/capita/day	–	–
Fuelwood	11 million hectares of forest and woodland Excess of 1.2 m ton/day	–	0.120 million ton/day
Animal waste	245 million assorted animals in 2001	–	0.781 million ton of waste/day
Agricultural residues	91.4 million ton/yr. produced	–	
Energy crops	28.2 million hectares of arable land (approx. 30% of total land)	–	0.256 million ton of assorted crops/day

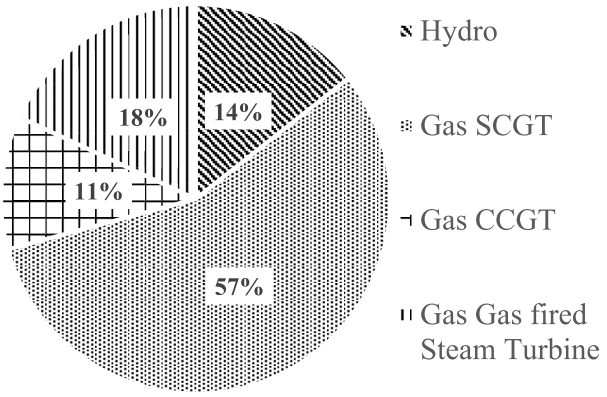

Fig. 3. Nigeria's power sector generation fuel mix (2018, Q3) [28,29].

Transmission System Provider (TSP) in the third quarter of 2018. This translated to a loss worth ₦1.90 of every ₦10 of electricity received mainly due to poor infrastructure from technical inefficiencies and energy theft from incessant illegal consumers. The financial liquidity challenge is also manifested in the revenue collection efficiency such that of the total billings, only 66% of the revenue was recovered in the same quarter. The DISCOs incurred a deficit of ₦108.4billion on the total invoice for both energy purchased and administrative services from the Nigerian Bulk Electricity Trading (NBET) and the Market Operator (MO) respectively [28].

The Energy Commission of Nigeria (ECN) estimates the capacity and average yearly expenditure on auto-generation (diesel and petrol generators) at about 2600 GW and ₦3.5 trillion per year with households amassing an expenditure of ₦1.56 trillion per year [32,33]. This gross underperformance has brought on severe electricity unavailability and financially bled the Nigerian economy across all sectors. The unreliable power supply has compelled many households, firms, and industries to resort to auto-generation of power with privately-owned generators for their electricity needs. This is to sustain their energy demand, production activities and capabilities even when these generators often proof to be expensive alternatives for energy production. Thus amassing twice the energy expenses (≈₦60 - ₦90/kWh; ≈$0.20/kWh - $0.29/kWh) than grid-connected power supply (typical DISCOs electricity tariff range of ≈₦20 - ₦48/kWh; ≈$0.065/kWh - $0.157/kWh) [20,34,35].

2.3. *A brief synopsis on rural electrification in Nigeria*

The inauguration of a nationwide rural electrification program in 1981 heralded the commencement of a rural electrification campaign in Nigeria. The defined target was to connect all 301 Local Government Area headquarters (LGA HQs) [36,37] to the central national grid. This effort was commendable as 78% of the 774 LGA HQs became grid-connected in 2005 [38]. However, this momentum was not maintained at the local network distribution front. The provided electricity coverage did not extend to surrounding hamlets and periphery local communities. The Federal Government of Nigeria sought to remedy this and in March 2005 birthed the Electric Power Sector Reform Act (EPSRA) from which the Rural Electrification Agency (REA) sprung forth. The REA managed the Rural Electrification Fund (REF) devoted to driving rural electrification programs and spurring the involvement of the private and public sectors. In 2009, the Nigerian government enacted the Rural Electrification Policy (REP) and charted its course of action in the Rural Electrification Strategy and Plan (RESP) in April 2015. The RESP mandated the Federal Ministry of Power (FMP) to draw up targets for rural electrification aligned with the National Electric Power Policy (NEPP). The government plans to provide electricity access to 75% of its entire population by 2020 and 90% of the entirety by 2030. It also plans to increase the share of renewable energy resources in the generation mix above 10% by 2025 [21]. The EPSRA mandated the REA to carry out new rural electrification projects and conclude ongoing projects initiated by the Federal Ministry of Power and Steel (FMPS) through the REP. The REA intends to implement various power projects including centralized energy systems (via grid extension) and decentralized energy systems (comprising mini-grids, and stand-alone systems). The REA regulates less than 1 MW electricity generation capacity and 100 kW distribution capacity for embedded power generation while the National Electricity Regulatory Commission (NERC) regulates between 1 MW and 20 MW of power generation. With respect to the development of mini-grid systems for rural electrification, the REA has adopted renewable resource-based energy systems of varying sizes and configurations. They include solar mini-grid system for clustered

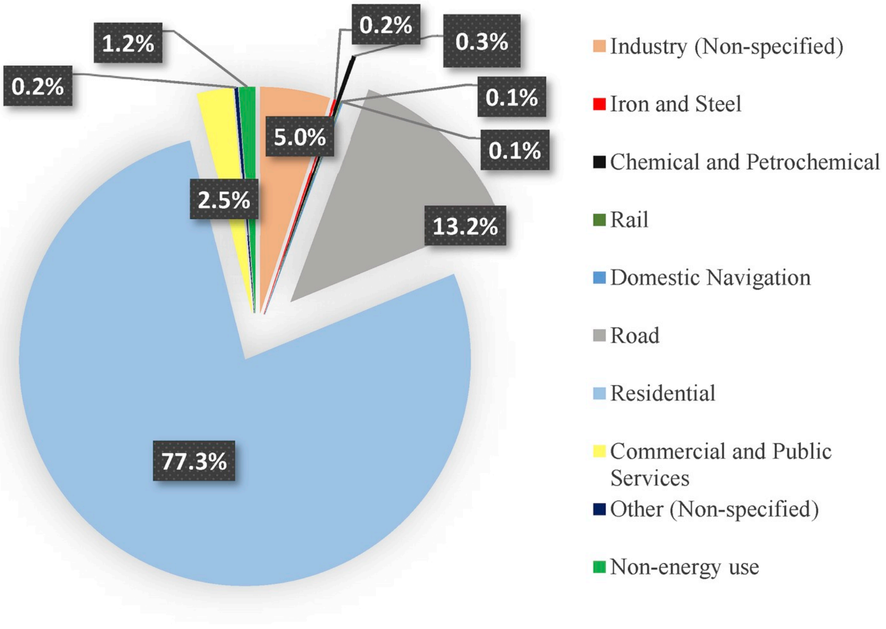

Fig. 4. Nigeria's Total Energy Consumption (TPEC) by sector (IEA, 2016) [30].

settlements; hydro systems: mini-hydro system (1–5 MW), micro-hydro system (100KW-990KW) and pico-hydro system (100W–300W); wind technology, biomass, and hybrid systems technologies [39].

Key stakeholders in the rural electrification sector include FMP, REA, NERC, state governments, and DISCOs. Identified barriers to rural electrification in Nigeria include policy harmonization, political will, funding, inadequate income-generating opportunities, insufficiently skilled local workforce, lack of sufficient planning and strategizing, etc [21,40]. Several policies and regulations have been deployed for renewable energy utilization as outlined in Table 3.

3. Extensive systematic literature review of Nigerian access energy studies

The employed methodology was based on an extensive systematic review of peer-reviewed literature encompassing relevant topics on Nigerian energy access studies. These included energy planning, energy access, electricity planning strategies, energy demand estimation, rural electrification, energy policy/reform and off-grid energy system studies. An initial basic literature search was carried out using the Google search engine. This afforded a link to other databases and platforms on which a thorough literature search was conducted. The literature search employed a combination of the keywords coined from the study areas. The range for the publication date was not rigid. Subsequently, a sorting and selection process was employed. Relevant papers pertaining to the topic were selected from various databases including Scopus, Google Scholar, Research Gate, Science Direct and Mendeley Personalised suggestions. Also, the references in relevant papers served as another information source for the methodical search. This resulted in a categorization of study areas into six main groups as shown in Fig. 5 and spread across a broad period ranging from 1978 to 2019. To enable a methodical selection process, the abstract of all the articles were read. The full articles of only relevant selections of each main group were read and included in the review. A total of 103 articles from 1978 to 2019 were discovered from which 90 relevant articles were selected and discussed. Only published articles comprising papers in international journals and proceedings from international conferences were chosen for this work. Statistics obtained are as shown in Figs. 6–9.

4. Overview of Nigerian energy access studies

This section expounds on the articles included in the review based on the elicited study areas.

4.1. Energy & electricity access impact

Energy access has maintained its undisputable significance as a paramount tool for attaining sustainable development. Indeed, energy access has far-reaching impacts on every facet of society and cuts across different sectors. A summary of relevant information contained in the selected papers is provided in Table 4.

The use of empirical indices and statistical analysis have been inculcated into different impact studies applied across different levels of disaggregation and application areas. Focussing on micro-enterprises, Ayodele et al. [51], developed four electrical energy indices bordering on electricity access, affordable electricity, suitable electrical appliance, and business location to inform intervention areas geared towards improving overall business productivity. These indices were applied to six prevalent micro-enterprises across 16 locations in Ibadan city, Nigeria. The results showed that electricity access and business location significantly impacted productivity even with the ownership of suitable electrical appliances. Also, electricity access emerged as the most critical intervention area across all investigated businesses. More so, to buttress the notion of electricity consumption promulgating economic growth, their inherent causal relationship was investigated in Ref. [47] in an aggregated nation-wide empirical study. It was found that there exists a one-directional causal relationship between electricity and economic growth in both the long and short-run. There was also a causal relationship between economic growth and inflation in the short run in both directions. Similarly, Riti and Shu [49] analyzed the causal links between energy efficiency and renewable energy (RE) and their direction of causality for fostering environmental friendly and sustainable energy access in Nigeria. They affirmed the prevalence of cointegration in both the long and short run in the nexus. Sanusi and Owoyele [48] utilized the Energy Development Index [EDI] to examine the relationship between energy access causal factors and energy poverty from both the state governments and households' perspective. Similarly, the Energy Use Index (EUI) was used to investigate the status and impact energy consumption of commercial buildings' (office buildings) exerts on the energy supply of the nation's capital, Abuja [43]. In Ref. [53], going beyond energy access and using Nigerian households as a case study, the relationship between energy mobility, living standards, and the economy was investigated by modeling the transition path from basic energy access to energy mobility. This proffered a scheme to enable households to derive optimum utility from the ownership and use of electrical appliances and facilitate policy formulation discussions on strategic electrification and pricing mechanisms to improve overall productivity.

Some authors investigated locational disparity and other issues related to modern energy access. Oyekale [42] used data from the 2008 Demographic and Health Survey (DHS) comprising over 34,000 respondents to examine factors impacting access to electricity and the adoption of modern cooking fuel sources in Nigeria. The overall household's access to contemporary energy sources was linked to energy supply reliability, household financial status, household size, gender, age, and education level. Also, some households could have an aversion to the risk and financial cost components of modern cooking fuels in addition to a cultural appeal for alternative cooking fuels. The incessant locational disparity (subnational and regional) was attributed to

Table 3
Existing energy policies and regulations in the renewable energy space [41].

Policy	Year	Status quo	Policy type	Defined target
Nigeria Feed-in Tariff for Renewable Energy Sourced Electricity	2016 (Feb)	In Force	Economic Tools (Fiscal/financial incentives, Feed-in tariffs/premiums)	Bioenergy, Solar, Wind
National Renewable Energy Efficiency Policy for Nigeria	2015	Planned	Policy Advocacy (Strategic planning)	All available renewable energy (RE) sources
Biofuels blending mandate	2013 (Dec31st)	In Force		Bioenergy (Biofuels for transport, Biodiesel, Bioethanol)
Multi-Year Tariff Order (MYTO) II (2012–2017)	2012 (June 1st)	Superseded	Economic Tools (Fiscal/financial incentives, Feed-in tariffs/premiums)	Wind (Onshore), Solar (Solar photovoltaic), Hydropower, Bioenergy (Biomass for power)
Nigeria Renewable Energy Master Plan	2011	In Force	Economic Tools (Direct Funding, Infrastructure investments, Fiscal/financial incentives, Tax relief), Policy Advocacy, Strategic planning	Wind, Bioenergy (Biomass for power), Solar (Solar photovoltaic), Hydropower, Multiple renewable energy Sources
Multi-Year Tariff Order (MYTO) I (2008–2013)	2008	Superseded	Economic Tools (Fiscal/financial incentives, Feed-in tariffs/premiums)	Multiple RE sources (Power)

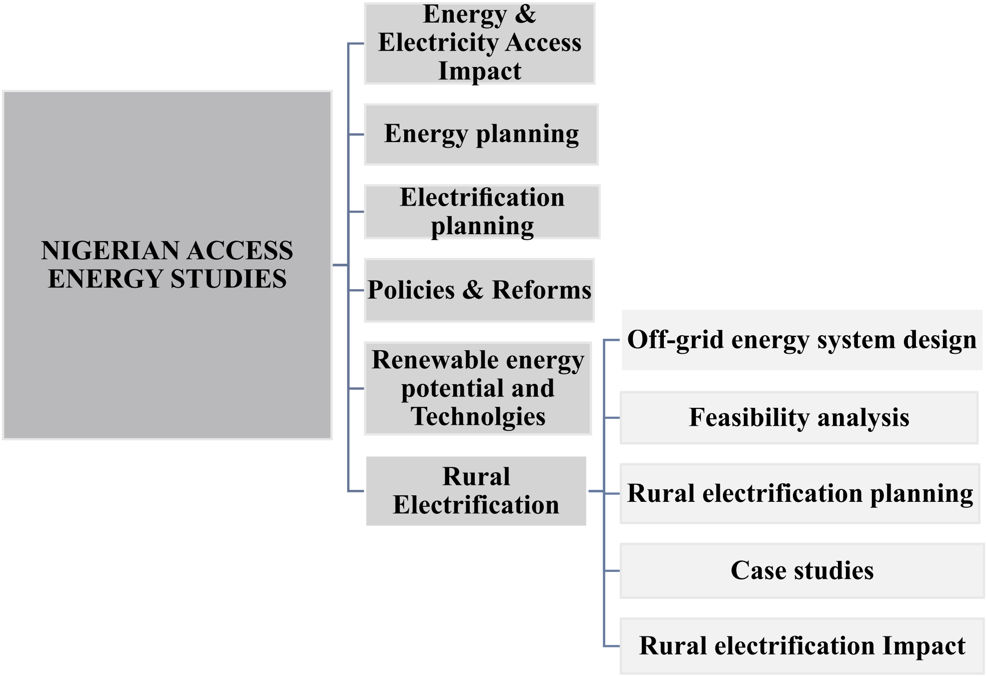

Fig. 5. Categorization of Nigerian energy study areas.

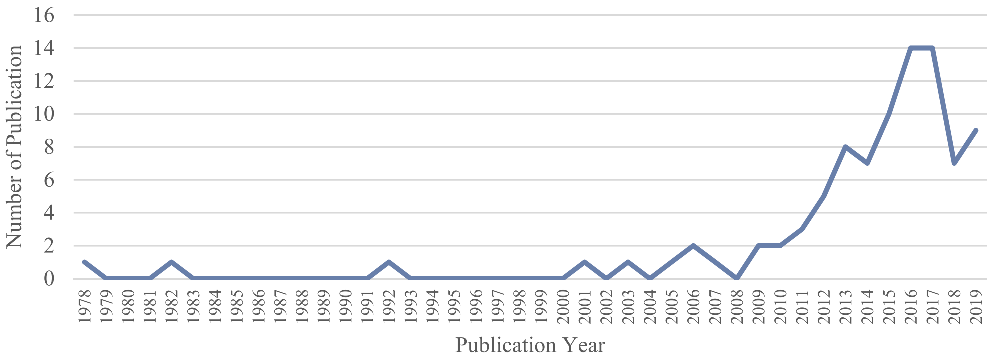

Fig. 6. Publication trend on Nigerian energy studies over the years.

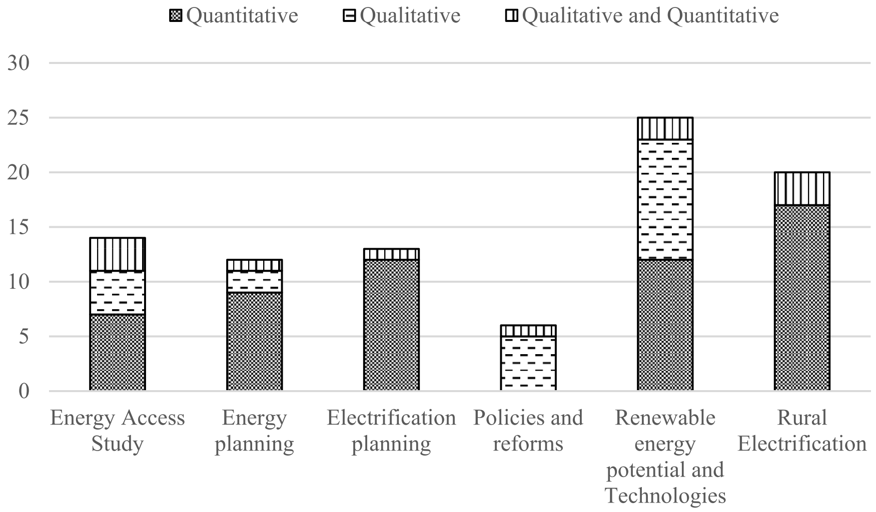

Fig. 7. Distribution of study areas by the type of analysis conducted.

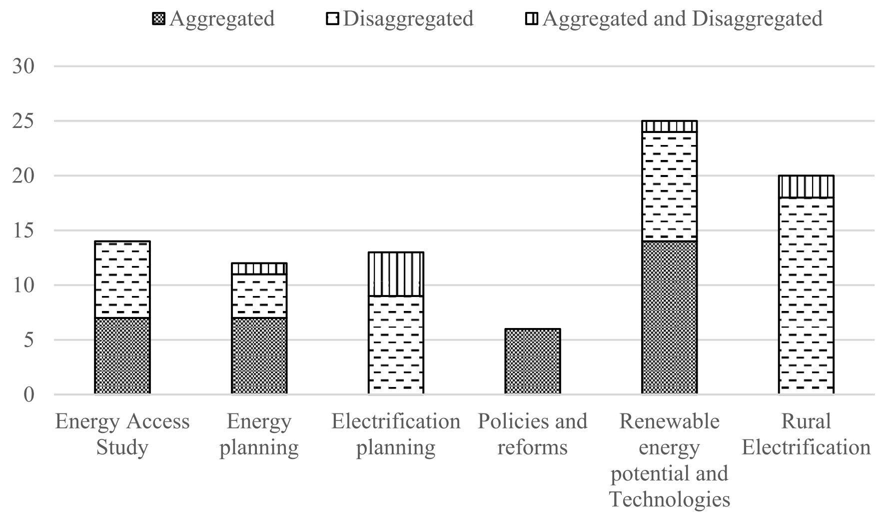

Fig. 8. Distribution of study areas by the level of aggregation (Spatial Coverage) considered.

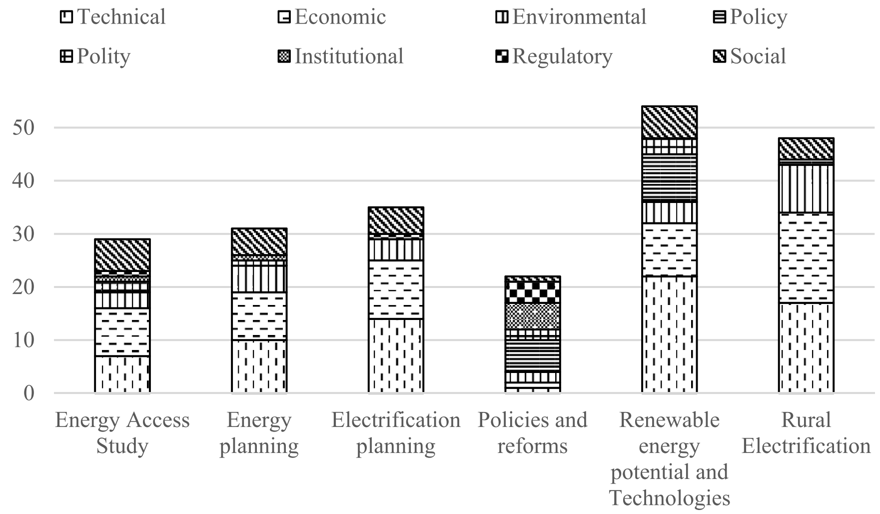

Fig. 9. Distribution of study areas by the criteria or dimensions considered.

successive Nigerian governments prioritizing urban energy access over rural energy access. Poverty incidence was more apparent in rural areas especially in Northern Nigeria. This position was further reiterated in Refs. [44,48] as households in Northern states recorded the least percentage for both electricity access and access to modern cooking fuels. Across five dimensions, Emodi et al. [45] identified several issues impinging Nigeria's electricity access including the technical and financial non-viability of the electricity sector across its entire value chain. Poor regulatory and institutional frameworks were identified as impediments to attracting investments in the sector. The polity and the government tenure system also rendered an unconducive business climate for investors. Additionally, a complete democratization of the Nigerian electricity sector was recommended for universal electricity access in Ref. [33] backed by "de factor" regulatory frameworks.

4.2. *Energy planning*

Several authors have coined different definitions for energy planning. Riva et al. describes energy planning as entailing systematic procedures for mapping out long-lived policies geared towards promoting actions on the conceptualization, actualization, and management of energy systems at varying levels from local, national to even global levels [55]. Coinciding with this definition, several energy planning studies have been undertaken to adopt varied planning horizons, energy models & approaches across different sectors as presented in Table 5.

The ECN adopting a top-down modeling approach carried out national energy planning studies to inform the conceptualization of a nationwide energy masterplan and a scheme for the expansion of the generation systems. They evaluated the nation's future energy demand and explored diversification strategies for the energy systems in the country. They reported problems of data intensiveness, inconsistent structure, and content of the MAED model with the Nigerian energy sector reality, uncertainties in the obtained results and issues regarding the implementation of the WASP model [27]. Ikpe and Torriti [65] assessed the viability of infusing demand-side management (DSM) for a nationwide campaign considering three industrialization scenarios. They outlined the interdependency between DSM, industrialization, and electrification from the perspectives of different cadres of end-users. Presuming Nigeria would supersede her millennium development goals (MDGs), Ibitoye [60] assessed the energy needs of Nigerian

Table 4
Selected Papers for the energy and electricity access impact tract.

Year	Paper	Methodology	Tool (Model or Software)	Sectoral Scope
2012	[42]	Descriptive statistics and Seemingly Unrelated Bivariate Probit (SUBP) regression.	STATA	Residential
2012	[43]	Case study approach	Energy Use Index (EUI)	Commercial
2012	[44]	NS	NS	Residential
2015	[45]	NS	NS	NS
2015	[46]	Energy partitioning approach	MATLAB	Residential
2015	[47]	Cointegration approach	Trivariate Vector Error Correction Models (VECM)	NS
2016	[48]	Energy Development Index [EDI] and regression analysis	NS	Residential
2016	[49]	Auto-regression distributed lag (ARDL) bound test cointegration approach and VECM-Granger causality test	EViews and STATA	NS
2016	[50]	Linear regression and correlation analysis	Statistical methods	Commercial
2018	[51]	Indices estimation approach	NS	Commercial
2018	[33]	NS	NS	NS
2018	[52]	Process tracing method	Multi-level perspective (MLP) theory	NS
2019	[53]	Modelling and Statistical indices	NS	Residential
2019	[54]	Exploratory approach	Socio-technical transition theory	Industrial

Note: NS = Note specified.

households based on three development plots. These included enhanced electricity access, refined living conditions in slums and ameliorated access to modern cooking fuels. From the result obtained, the household demand for electricity would be increasing along with the demand for modern cooking fuels thus resulting in raising the level of accumulative non-biogenic CO_2 emissions. Similar scenario analysis studies were conducted in Ref. [66] to quantitatively examine the United Nations'-SE4ALL initiative as it would impact Nigerian households.

The study by Emodi et al. [63] was the first of its kind to employ a bottom-up approach for exploring feasible pathways for actualizing a vibrant performing energy sector in Nigeria. They developed an energy model for Nigeria and strategies to prospect the future energy demand, supply, and the accompanying greenhouse gas (GHG) emissions. They considered four scenarios namely: the reference scenario (REF), the low-carbon moderate scenario (LCM), the low-carbon advanced scenario (LCA), and the green optimistic scenario (GO). They understudied the effect of several energy policies on the nation's energy system and performed a cost-benefit analysis (CBA) of the different system configurations. Overall, they sought to come up with realistic developmental frameworks geared towards accomplishing sustainable development in Nigeria. Significant improvement in energy demand and GHG reduction were attainable under all the scenarios. However, the GO scenario presented a more optimistic amelioration trajectory geared towards achieving and sustaining low-carbon development for Nigeria. It presented a higher propensity for reducing GHG emissions based on the implementation of sector-specific policies and strategies. The residential and transport sectors are salient areas for proliferating low-carbon development strategies in Nigeria. The industrial and commercial/service sectors would also benefit from perusing future initiatives targeting the reduction of energy consumption and GHG emissions. From the CBA results, the enforcement of the different policies would accrue high investment costs to cater for energy efficiency, changing fuel options, etc. These costs could be somewhat offset by the dividends realized from savings on the energy user's end in connection to power generation and environment protection externalities. Aliyu et al. [67] investigated Nigeria's power generation expansion plans together with the accompanying environmental ramifications of building a nuclear power plant as a power generation alternative. Based on three different scenarios that considered the national projected growth rates of the peak load, the electricity demand and the global warming potential (GWP) were

Table 5
Selected Papers for the energy planning tract.

Year	Paper	Methodology	Tool (Model or Software)	Sectoral Scope	Dimensions or Criteria	Temporal coverage
1978	[56]	Non-convex mathematical programming	Zero-one (O-l) MIP	NS	Technical, Economic	Long-term (1975–2004)
1982	[57]	NS	NS	NS	Technical, Economic, Polity, Social	NS
2006	[27]	Energy system Modelling and Scenario Analysis	MAED and WASP	Residential, Services, Industrial, Transport	Technical, Economic	Long-term (2000–2030)
2006	[58]	Energy Demand Estimation and Scenario Analysis	Excel	Industrial, Agricultural, Services, Residential	Technical, Economic	Long-term (2006–2030)
2010	[59]	Scenario Analysis and LCA	GEMIS and SimaPro	NS	Environmental, Economic, Technical	Long-term (2003–2030)
2013	[60]	Energy system Modelling and Scenario Analysis	LEAP	Residential	Environmental, Technical, Social	Long-term (2005–2020)
2013	[61]	Energy system Modelling and Scenario Analysis	LEAP and AERMOD 12,345	NS	Economic, Environmental, Technical	Long term (2010–2030)
2015	[62]	Energy system Modelling and Scenario Analysis	STAMP, STSM, UEDT, and APR	NS	Social, Economic, Environmental	Long-term (1971–2025)
2017	[63]	Energy system Modelling and Scenario Analysis	LEAP	Residential, Commercial, Service, Industrial, Agricultural, Transport	Environmental, Economic, Technical, Social	Long-term (2010–2040)
2017	[64]	Exploratory analysis	NS	NS	Institutional	NS
2018	[65]	Energy system Modelling and Scenario Analysis	MARKAL	Services, Residential, Transport, Industrial, Agricultural	Technical, Economic	Long-term (2000–2050)
2019	[66]	Energy system Modelling and Scenario Analysis	LEAP	Residential	Technical, Environmental, Social	Long-term (2010–2030)

Note: MARKAL = MarKet and Allocation, LEAP = Long-range Energy Alternatives Planning, MAED = Model for Analysis of Energy Demand, WASP = Wien Automatic System Planning, MIP = Mixed integer programming, Global Emissions Model for integrated Systems = GEMIS, life cycle assessment = LCA, Atmospheric dispersion module model = AERMOD 12,345, Structural time series analyser and modeller and predictor = STAMP, Structural time series model = STSM, Stochastic underlying energy demand trend = UEDT and Asymmetric price response = APR.

forecasted. In Ref. [68], four exploratory scenarios encompassing fossil-fuel (FF), combined-cycle gas turbine (CCGT) and sustainable development driven scenarios (SD1 and SD2) for the Nigerian power sector were analyzed. The FF scenarios provided the lowest capital costs for expanding electricity access at the expense of elevated adverse environmental impacts. Both the SD1 and SD2 scenarios mitigated these impacts with the increased share of renewables but at the cost of a significant increase in capital investment.

Ibitoye and Adenikinju [58] examined the likely trend in Nigeria's electricity demand over the next 25 years. They presumed that Nigeria would undergo rapid economic development to transform from a low-income to a middle-income economy, meet her MDGs by 2015, and achieve the status of industrialization at all levels. They analyzed the funding requirements to actualize these presumptions. They also provided that the financing structure comprised of capital expenditure accounting, operating expenditure and electricity generation costs and gas transmission and distribution. Tajudeen [62] made a case for including non-economic aspects such as consumption behaviors, preferences and overall disposition in addition to energy efficiency into energy demand modeling. He examined the impact of socio-cultural factors and energy efficiency on modeling energy demand and CO_2 emissions for Nigeria using a combination of three different empirical modeling approaches. Ayodele [69] investigated the technological choice for decision-making processes based on the interplay between technological, economic, social and political criteria for power plant generation projects using a hydropower plant project case study. He reiterated the significance of the social and economic dimensions and buttressed on modalities from the political dimension that can impact socio-economic aspects of the decision-making process. Iwayemi [56] analyzed issues pertinent to efficient financial resource allocation in the economies of scale space. His efforts were mostly targeted at informing the long-term funding decisions undertaken by the Federal government sect of the power industry (formerly solely manned by NEPA and now partly by PHCN). This planning issue espoused determining the most viable energy system infrastructure mix to abate the shortcomings of existing systems at reduced costs. Edomah [64] analyzed the institutional framework of the electricity industry across 9 developing countries and proposed a new organizational model for the Nigerian electricity supply market.

4.3. *Electrification planning*

One resonating definition of electricity planning was proposed by Trotter et al. [70]. They regarded electricity planning as infusing a coherent and holistic method to foster a balance between electricity demand and viable electricity supply. This will take into cognizance the interactions of economics, technology, social aspects, environment and political dispensation at varied levels. Also, this interplay must be within at least one of the electrification value chain context. These include technology designation, system and network configuration, operation planning, demand estimation and understudying the grounds for seamless energy system implementation. As such, several electricity planning models with different characteristics and elements have been developed and applied to Nigeria (see Table 6) to address a variety of electricity planning objectives and value chain.

Bertheau et al. [75] devised optimization paths for achieving rapid nationwide electrification. Their approach involved identifying clusters for different types of consumers, deducing the status quo on electrification and then allotting electricity supply options among three viable alternatives namely: Grid extension, photo-voltaic (PV)-hybrid mini-grids and solar-home systems (SHS). They discovered that within a

Table 6

Selected Papers for the electrification planning tract.

Year	Paper	Methodology	Tool (Model or Software)	Sectoral Scope	Dimensions or Criteria	Temporal coverage	Optimal configuration
2014	[71]	Simulation and Optimization	HOMER and Solectria String Sizer	Residential	Economic, Technical	Short-term (1 year)	PV array: 80kW/Inverter: 85kW/Grid: 100 kW
2015	[72]	Spatial electricity planning and modelling	NP	Residential	Technical, Economic, Social	Long-term (2013–2030)	Solar PV/DG
2015	[73]	Geo-spatial electrification assessment	GIS and Excel (VBA)	Residential	Technical, Economic, Social	Long-term (2015–2030)	PV/Wind/Hydro/DG
2015	[74]	Geo-spatial modelling and Simulation	NP	Residential, Commercial, Service	Technical, Economic, Social	Medium-term (10 years)	PV/DG
2016	[75]	Geo-spatial modelling and Simulation	GIS	Residential	Technical	NS	NS
2016	[76]	Multi-step mathematical programming approach (RE system design)	Integer LP tool	Residential	Technical	NS	SPs and SWAPs (Total Capacity): 15 MW
2016	[77]	Simulation and System Optimization	HOMER	Industrial	Economics, Environmental, Technical	Short-term (1 year)	PV array: 50 kW/Inverter: 10kW/DG: 10 kW
2017	[78]	LCI assessment	NS	Residential	Technical, Environmental, Economic	Short-term (1 year)	PV array: 1.5 KW/DG: 1.5kVA
2018	[79]	Consumption estimation approaches and Scenario Analysis	NS	Residential	Economic, Social	Short-term (1 year)	NS
2019	[80]	Simulation and Optimization	HOMER and Excel	Residential	Economics, Environmental, Technical	Short-term (1 year)	PV array: 0.3–76 kW/Battery: 2–176 kWh/Inverter: 0.1–13.2 kW
2019	[81]	Simulation and System Optimization	HOMER	Commercial, Service	Technical, Economic	Short-term (1 year)	NS
2019	[82]	Simulation and System Optimization	HOMER	Commercial, Service	Economic, Social, Technical, Environmental	Short-term (1 year)	NS
2019	[83]	Geo-spatial modelling and Simulation	GIS and HOMER	Residential	Economic, Technical, Regulatory	Short-term (1 year)	PV array: 3280 MW/Battery: 7518 MWh

Note: HOMER = Hybrid Optimization Model for Electric Renewable, NP = Network Planner, VBA= Visual Basic for Applications, LP = linear programming, LCI = Life cycle impact, Diesel Generator = DG, Standalone = SA, Solar Parks = SPs, Solar and Wind-Assisted Parks = SWAPs, Solar-home systems (SHS).

buffer zone of 20 km, grid extension would have the maximum impact of delivering electricity. Outside this zone, PV-hybrid mini-grids and SHS were more suitable for delivering electricity to customer clusters. A similar but pioneer study was conducted by Arowolo et al. [83] on mapping out localized electrification pathways for mini-grid systems and the obtained results provide support for building business portfolios, business cases for investors and designing mini-grid auctions. Mentis et al. [73] developed a GIS-based method to proffer schemes and strategies for performing electrification planning. This was then applied to Nigeria to pinpoint the most economical and feasible electrification recourse comprising grid network augmentation and off-grid autonomous systems. They illustrated how these choices were impacted by cost factors (technology costs, fuel costs, tariff scheme), power system infrastructure, economic dispensation, and population density. On-grid connections would offer the most practical option for densely populated and non-remote localities. Remote localities with low population densities favored off-grid solutions. Ohiare [72] carried out a nationwide electrification planning study. He mapped out the most feasible electrification roadmap and electricity supply track with the associated costs. The obtained results reiterated the findings in Ref. [73] in terms of the most economical electrification strategy. These results also provided the foundation upon which the REA developed their rural electrification roadmap and co-ordinated their activities. Between 2013 and 2017, about 250 kW off-grid energy systems were deployed comprising solar PV and biogas mini-grid systems serving approximately 10,200 people [84]. Also, this has facilitated the conception of a national electrification project to spur the rapid development of the off-grid energy sector [85].

Some studies have been conducted at lower disaggregation levels. Akpan [74] investigated cost-effective technology alternatives to enhance electricity access across two Nigerian states, Taraba and Yobe. These states recorded some of the worst electrification rates in the country just under 20%. He analyzed three electrification alternatives namely: grid expansion, mini-grid hybrid systems, and unaccompanied or stand-alone systems comprising solar PV and/or a small diesel generator. The obtained results also showed that grid-expansion was the most economic option for the demand nodes (electoral wards). Due to the non-granularity of these nodes, the results were not more detailed as there was no available data at more segmented administrative levels. Several studies have been carried out using the feasibility studies approach. In Ref. [80], the viability of localized onsite electricity generation was assessed for standalone operation. This study was supported by real electric load data from structured time of use surveys. Specific case studies [77,81,82] adopted the feasibility studies approach in addition to local RE resource assessment [78]. Ikejemba and Schuur [86] developed a multiple-stage mathematical programming approach for situating localized RE Parks (Solar Parks (SPs) and Solar and Wind-Assisted Parks (SWAPs)) to inform the planning of localized autonomous energy supply networks.

4.4. Policies and reforms

Judicious “de facto” energy policies are pivotal in charting the course of action onto more sustainable development routes. The Nigerian government executed some reforms across the power sector. The cardinal objectives are to improve the nation’s electricity access and supply reliability and realize universal electricity coverage within the fastest conceivable timeframe [74]. Some authors have carried out detailed analyses of the overall energy policy spectrum and specific policies and reforms as outlined in Table 7.

Ikeme and Ebohon [87] examined the power sector reform proposed for Nigeria and suggested some reform objectives. These included corporatizing the power generation industry, enhancing energy security, availability and power distribution capacity, curtailing all-round energy costs and encouraging efficiency and the adoption of renewable resources in energy generation. The paradigm upon which the policy reforms were conceived spanned regulatory institutions and funding schemes namely: the National Electricity Regulatory Commission (NERC), the Rural Electrification Fund (REF), and the Consumer Assistance Fund (CAF). They communicated their pessimism that proposed reform efforts will not produce the anticipated results due to the alarming levels of consumer-end inefficiency. This reflects the reality of the Nigerian energy sector (see section 2.2). Usman et al. [90] reviewed the performance of the power sector taking circumspect of the implemented policies and reforms. They reported the persistence of an underwhelming performing sector irrespective of government-initiated strategies geared towards reinvigorating the sector. They opined that Nigeria is lagging in terms of energy efficiency visions, targets, and laws. They advocated for policies and reforms compassing the building blocks of world energy issues monitor proliferated by the World Energy Council (WEC). The recommended inculcating energy efficiency & renewable energy uptake coupled with the success formula of other countries (Brazil and India) with similar peculiarities.

In Ajayi et al. [88], the emphasis was on nationwide RE development. Excerpts from RE policy statement including the Renewable Energy Master Plan (REMP) were examined. Up to date, there have not been recorded any large-scale electricity supply from other RE resources than the pre-existing hydropower plants. Ohimain [89] carried out a comprehensive assessment of the policy framework for bioenergy development particularly the Nigerian biofuel policy to identify discrepancies, flagrant omissions and inherent policy gaps such as would warrant a revision of the policy. Edomah et al. [92] examined the governance regime and policy process of the Nigerian electricity sector as regards infrastructure developments. They elicited intra-country factors impacting the sector’s performance especially political power play. Gana and Hoppe [91] reviewed energy efficiency policies and the associated governance framework related to household electrical appliances. The consensus was that there is no existing policy mandate for the aforementioned subject. Non-committal actions from the government in terms of resource allocation and inadequate stakeholder involvement (household sect) have reinforced this consensus.

4.5. Renewable energy potential and technologies

Table 8 presents a comprehensive list of studies carried out on RE potential and affiliated technologies.

Considering the decrepit state of the Nigerian electricity sector, Akuru et al. [117], concluded that deliberate measures must be put in place to aid the nation’s transition from conventional energy sources to renewable energy and environmentally friendly sources. Indeed, this

Table 7

Selected Papers for the policies and reforms tract.

Year	Paper	Tool (Model or Software)	Paper Focus	Dimensions or Criteria
2005	[87]	NS	Electric Power sector reform	Institutional, Regulatory, Policy
2013	[88]	NS	Policy framework for RE development (The Renewable Energy Master Plan)	Policy, Environmental
2013	[89]	NS	Biofuel Policy and Incentives	Technological, Policy, Institutional, Regulatory, Environmental, Social, Economic
2015	[90]	NS	Power sector performance	Policy, Institutional
2017	[91]	Governance Assessment Tool (GAT)	Policies and governance regime (Energy Efficient Household Appliances)	Policy, Institutional, Regulatory, Polity
2017	[92]	Interview protocol	Electricity sector governance	Policy, Institutional, Regulatory, Polity

transition is critical for national development and may be more easily driven by individuals and private businesses than the Federal Government. They highlighted different renewable energy sources and their affiliated costs pivotal for solving the electricity generation problem in Nigeria. Shaban and Petinrin [105] carried out a nationwide review of the renewable energy potential to expound the extensiveness of these resources. They proposed policies that could engender the wide adoption of renewable energy in rural Nigeria. Oyedepo et al. [31], carried out a comprehensive review of the RE resource potential in Nigeria to examine their appropriateness for implementing decentralized energy systems to electrify rural areas and urban locations not yet connected to the national grid. They concluded that these systems would be sustainable in the long term when a participatory approach involving all stakeholders in all the critical project phases is embraced.

Some authors have focussed on some RE resources and site-specific case studies for RE resource assessment. In a comprehensive review of green energy potential, applications and renewable energy policies in Nigeria, Giwa et al. [41] presented solar and biomass resources due to their huge availability. They elicited that the techno-economic feasibility and viability of utilizing these resources for sustainable development is location-dependent and contingent on key aspects. These aspects included financial, institutional, cultural, educational, political and social imperatives. The assessment of small hydropower (SHP) development in Nigeria was carried out in Ref. [98] where a case was made for further exploitation of Nigeria's vast small hydropower potential. In Ref. [106], current perspectives on solar energy utilization (its applications and development) was investigated within a sustainable development framework. An appraisal of solar energy potential across three strategic urban locations was performed in Ref. [108] to advocate for the implementation of standalone PV systems in the residential sector. In Ref. [115], a hybrid artificial neural network (ANN) method was adopted for solar resource assessment and forecast in seven locations spread across the different climatic zones in Nigeria. Ozoegwu et al. [112] evaluated the integration of solar energy in Nigeria to substantiate the global precedence availed to solar energy resources above other renewable resources. They buttressed on the opportunity to explore large scale on-grid solar energy development. Suberu et al. [102]. carried out an analysis on the potential of municipal solid waste (MSW) for renewable power generation in the Lagos metropolis of Nigeria. They reported probable added benefits of financial recompense, efficient waste handling and freed up land for other productive uses. In Ref. [103] localized assessment of wind energy potential and viability of wind energy conversion systems were carried out across six locations. They compared the performance of different wind turbine models. The same approach was applied in Ref. [101] for assessing the feasibility of powering a water pumping system using wind energy.

4.6. Rural electrification

Electrification is one of the most proactive steps within our withal to

Table 8
Selected Papers for the RE potential and technologies tract.

Year	Paper	Tool (Model or Software)	Paper Focus	Dimensions or Criteria	RE resource type
1992	[93]	NS	Estimation of Wind Potential	Technical	Wind
2007	[94]	Wind Energy Tool Box (Weibull distribution) and CBA	Wind energy conversion technologies	Technical, Economic, Environmental	Wind
2009	[95]	NS	Energy supply resource mix	Technical	Solar, Wind, and Hydro
2009	[96]	MATLAB's Neural Network Toolbox and GUI and ArcView	Modelling and Mapping of global solar radiation	Technical	Solar
2010	[97]	MATLAB's Neural Network Toolbox and ArcView	Modelling and Mapping of wind speed	Technical	Wind
2011	[98]	NS	SHP Potential	Technical, Policy, Economic	Hydro
2011	[99]	2-parameter Weibull probability distribution function	Estimation of Wind Potential	Technical	Wind
2011	[100]	2-parameter Weibull probability distribution function	Estimation of Wind Potential	Technical	Wind
2012	[101]	Weibull probability function and LCOE	Water pumping system powered by wind energy	Technical, Economic	Wind
2012	[102]	NS	MSW for electricity generation	Technical	Biomass (MSW)
2013	[103]	Weibull probability function, LCOE, and PVC	Wind energy conversion technologies	Technical, Economic	Wind
2013	[104]	IPCC Mathematical model	Bioelectricity from biogenic methane	Technical, Social, Economic, Polity	Biomass (animal manure and MSW)
2014	[105]	NS	RE for rural energy needs	Policy, Social	Solar, Hydro, Biomass, Wind
2014	[106]	NS	Solar energy Development	Economic, Policy, Social	Solar
2014	[107]	SEI	Geothermal resource categorization	Technical	Geothermal
2016	[108]	Isotropic sky model and LCCA model	Solar energy Development	Technical, Economic	Solar
2016	[109]	NS	Biofuel potential as transportation fuels	Technical, Policy, Social, Economic, Environmental	Biomass
2017	[110]	NS	RE Energy Generation	Technical, Economic, Polity	Solar, Hydro, Biomass, Wind
2017	[111]	NS	Solar and Bioenergy Development	Technical, Policy, Social, Economic, Environmental	Solar, Biomass
2017	[112]	NS	Solar Integration status	Technical, Policy	Solar
2017	[113]	NS	Agriculture sourced RE	Technical, Environmental, Policy	Biomass (agriculture sourced and MSW)
2017	[114]	Mixed-method approach (TRA and TAM) and SPSS	Public perception of RETs	Social	NS
2018	[31]	NS	Decentralized RE	Technical, Policy	Solar, Hydro, Biomass, Wind
2019	[115]	MATLAB's GUI and Hybrid ANN MATLAB code	Modelling and Mapping of global solar radiation	Technical	Solar
2019	[116]	REUF	RETs for power generation	Technical, Policy	Solar, Hydro, Biomass, Wind, Hydrogen

Note: CBA = Cost benefit analysis, GUI = Graphical user interface, levelized cost of electricity = LCOE, MSW = Municipal Solid Waste, PVC = Present value cost, IPCC = Intergovernmental Panel on Climate Change, SEI = Specific Exergy Index, SHP = Small hydropower, LCCA = Life cycle cost analysis, TRA = theory of reasoned action, TAM = technology acceptance model, RETs = Renewable energy technologies, REUF = Renewable energy utilization framework, ANN = Artificial Neural Network.

upgrade the livelihoods of people dwelling in rural areas. Given Nigeria's geography, it is not economically viable to supply electricity to remote rural communities by extending the national grid. This would require enormous financial commitments to procure high voltage transmission lines and medium or low voltage distribution lines [73,83]. Some studies reiterated that off-grid systems are the most economical routes for delivering electricity to rural dwellers. Also, these systems would be based on RE resources ([74,118]). Therefore, diverse studies have been carried out in this regard on varied scales and analyses ranging from off-grid energy system design, feasibility analyses, rural electrification planning to rural electrification impact studies as presented in Table 9.

Regarding off-grid energy system design, Ghavidel et al. [139] designed a Pump as turbine scheme as a management strategy for the water and electricity nexus. This served to provide water and electricity for domestic and productive uses in remote rural settlements at reasonable costs. Olatunji et al. [121] investigated the efficacy of the hydrokinetic turbine technology to provide electricity access to a rural civic center based on the potential of the technology for small-scale electricity generation. A solar chimney power plant was adopted for large-scale electricity generation in rural settlements in Ref. [120]. Feasibility analyses encompassed technical and economic assessment of decentralized hybrid energy systems. In Ref. [125], the optimal configuration of off-grid systems were investigated for electrifying six rural communities. Other analyses included evaluating the economic viability of different configurations of standalone hybrid energy systems [123]; the economic viability of embedded generation energy systems [140], and costs comparison between centralized and decentralized generating systems of various capacities and configurations [141]. Concerning case study analyses, a decentralized energy hub for community residents was designed by Nna et al. [133] to avail rural energy access for broad productive utilization in wide applications within the community; Olatomiwa et al. [132] and Anayochukwu et al. [142] presented the optimum hybrid energy system configurations for rural healthcare facilities. An optimal power system was designed for off-grid voter registration centres in Ref. [143]. Baek and Jung [135] carried out rural electrification planning to forecast the electricity supply and demand in the residential sector, under three scenarios namely: Energy Efficiency (EE), Renewable Energy (RE), and Combined Policy (CP). The marginal abatement cost (MAC) curve was applied to highlight policy precedence for low carbon options. The CP scenario offered the most viable option in terms of both cost and CO_2 emissions. The crucial aspect of local demand assessment for the planning framework of rural electrification was addressed by Adeoti et al. [134] in their study such that the load demand was estimated for both electrified and non-electrified households at disaggregated end-use levels of lighting and electric appliances. Rural electrification impact studies were carried out including the evaluation of the impact of rural electrification on the well-being of

Table 9
Selected Papers for the rural electrification tract.

Year	Paper	Tool (Model or Software)	Application area	Dimensions or Criteria	Temporal coverage	Energy System type	Optimal Configuration
2016	[119]	MGSA and RWM	Rural communities	Economic, Technical	NS	Hybrid	PV array:10.39 m^2/DG: 27kW/WP: 3.1kW/ Batteries: 15.49 kWh/WS: 23.2m^3
2017	[120]	NS	Rural communities	Economic, Technical, Environmental	NS	SCPP	Solar collector/Turbine/Chimney
2018	[121]	NS	Rural civic center	Technical	NS	Hydrokinetic system	Hydrokinetic turbine: 2.5kW/Batteries: 350Ah/ water velocity: 1.2 ms^{-1}
2003	[122]	NS	Rural communities	Economic, NS Technical		Centralized and Decentralized SHS	Decentralized SHS: 300W
2014	[123]	HOMER and RET Screen	Rural communities	Economic, Technical	Short-term (1 year)	SA hybrid	PSS- PV array: 135kW/Converter: 35kW/ Batteries: 1118 kWh; WSS- Wind: 50kW/DG: 10kVA/Converter: 35kW/Batteries: 464 kWh
2014	[124]	HOMER	Residential	Economic, Technical, Environmental	Short-term (1 year)	SA hybrid PV -diesel	PV array: 175kW/DG: 260kW/Converter: 150kW/ No. of Batteries: 100 units
2015	[125]	HOMER	Rural communities	Economic, Technical, Environmental	Short-term (1 year)	Hybrid	PV array: 8–20kW/DG: 10–15kW/Converter: 5–10kW/No. of Batteries: 32 units
2015	[126]	HOMER	Rural communities	Economic, Technical	Short-term (1 year)	SA PV (embedded generation)	PV array: 15 MW
2016	[127]	HOMER and TOPSIS	Rural communities	Technical, Economic, Social and Environmental	Short-term (1 year)	Hybrid	PV array: 25000kW/DG: 25000kW/Wind turbine: 25000kW/Converter: 15000kW/Batteries: 40000 kWh
2017	[128]	HOMER	Rural communities	Economic, Environmental, Technical	Short-term (1 year)	Decentralized Micro-grids	NS
2017	[129]	HOMER	Residential	Economic, Technical	Short-term (1 year)	Hybrid Nano-grids	PV array: 2.5–7kW/DG: 2.5–5kW/Wind turbine: 1.8–3.6 kW
2013	[130]	HOMER	RHC	Economic, Technical, Environmental	Short-term (1 year)	Hybrid	PV array:5kW/DG: 2.5kW/Batteries: 24 units/ Converter: 19 kW
2014	[131]	HOMER	VRC	Economic, Technical	Short-term (1 year)	PV-Battery system	PV array: 0.9kW/Inverter: 1kW/No. of Batteries: 9 units
2016	[132]	HOMER	RHC	Economic, Technical, Environmental	Short-term (1 year)	Hybrid	PV array: 3–5.5kW/Wind: 1–2kW/DG: 3kW/ Converter: 1–3kW/No. of Batteries: 10–20 units
2016	[133]	NS	Rural community energy hub	Economic, Technical, Environmental, Social		Hybrid	PV array: 8kW/DG: 10kVA/Inverter: 10kVA/ Batteries: 3500Ahr
2001	[134]	NS	Residential	Technical	NS		
2016	[135]	LEAP and MAC curve	Residential	Environmental, Economic, Technical, Policy	Long-term (2010–2030)		
2013	[136]	EViews	Commercial	Economic			
2016	[137]	CBBH model	Residential	Social			
2017	[138]	FGTT, STATA	Residential	Economic, Social			

Note: MGSA = Modified Gravitational Search Algorithm, RWM = Roulette Wheel Mechanism, DG = Diesel Generator, WP = Water Pump, WS = Water Storage, SCPP = Solar chimney power plants, SHS = Solar home system, PSS = PV standalone system, WSS = Wind standalone system, SA = Standalone, TOPSIS = The Technique for Order of Preference by Similarity to Ideal Solution, RHC = Rural health clinics, VRC = Voter Registration Centres, MAC = Marginal abatement cost, CBBH = Copula-based bivariate hurdle, FGTT = Foster Greer Thorbecke technique.

rural households in Ref. [138]. In Ref. [137], they investigated the impact of rural electrification on household labor supply. They also considered the underlying causal effect of electrification as a technical shock that could impact household time allocation from a gender perspective [137]. Akpan et al. [136] provided that the productivity of rural businesses was impacted by electrification so much so that rural business owners were willing to pursue alternative electrification options irrespective of associated costs.

5. Discussion

From the publication trend (Figs. 6), 90% of the papers were published from 2009 to 2019 even with an unconstrained literature search in which the publication dates were not fixed. This could be attributed to raised awareness levels by virtue of the advent of the UNs Sustainable Development Goals (SDGs) in 2015 since the number of publications peaked after 2015. Early publications provided a base for future work to be conducted. Thus, providing more leverage on which recent studies were carried out and this contributed to the observed trend. Given the multifaceted and multi-disciplinary nature of energy access studies, it was fitting to have arrived at a wide pool of 45 publication outlets. Most articles were published in the Renewable and Sustainable Energy Reviews and Renewable Energy and Energy Policy journals.

Overall, it was observed that most publications favored quantitative approaches (57 out of 90 papers) than qualitative approaches or a combination of both. However, this was not the case when taking circumspect of the individual study areas (see Fig. 7). Qualitative approaches that entailed comprehensive review and discourse analysis were relegated to papers in the Policy and reforms and Renewable energy potential and Technologies track. This reinforced the assertion that qualitative approaches were much more suited to these study areas [70]. Also, papers that adopted qualitative approaches considered more study dimensions for their analyses such that encompassed a range of one to seven with an average of three study dimensions per paper. There was a plethora of methodologies adopted (See Tables 4–9) for quantitative analyses and a combination of both approaches ranging from various statistical analyses, mathematical modeling, simulation, optimization, behavioral modeling, system analysis, decision support, and life cycle approaches. However, these employed fewer study dimensions at an average of two per paper.

With reference to spatial coverage, studies were carried out at varying levels of aggregation (Fig. 8) namely; aggregated and disaggregated levels. Aggregated levels encompassed nationwide studies. Disaggregated levels focused on specific locations at varying levels including sub-national (rural or urban), regional (specific geopolitical zones or administrative domains) and local (specific cities, villages, communities etc.). Disaggregated studies have been mostly carried out (53% of the selected papers). Many authors favored disaggregated level studies especially as they often avail more insights and perspectives than a country-level approach and opportunities to proffer new perspectives and understanding on intricacies of Nigerian energy access that were not previously considered ([50,51,76,81,82,91,114,121,126]).

Eight different study dimensions or criteria were considered across the studies carried out as shown in Fig. 9, namely technical, economic, environmental, policy, polity, institutional, regulatory and social dimensions. The technical dimension dealt with system design, technology selection and assessment. The economic dimension considered diverse financial perspectives taking cognizance of the different costs' factors and their affiliated ramifications. The environmental dimension considered the emissions and associated impact from different energy system technologies and configurations. The social dimension considered the influences of urban and rural disparities, gender and education levels, people's perception and behaviors. Polity dimension addressed the political climate for investments, the interplay of political will, political interference and varied interest in decision-making processes. The institutional and regulatory dimensions took cognizance of multi-stakeholder involvement, the governance framework, and inadequacies of existing regulatory structure and scheme. The policy dimension addressed the inefficiencies of the existing policies framework and assessed their effectiveness in terms of implementation. Overall, the technical dimension was most frequently included across the study areas (32% of the selected papers) followed by the economic (26%), environmental (12%) and social (12%) dimensions. The regulatory (3%) and institutional (3%) dimensions were the least considered dimensions. 31% of the studies considered two dimensions while 29% considered three dimensions. Most papers favored the combination of these top four dimensions in the studies conducted. This inadvertently sets the precedent for future energy access studies such that principally considers these four dimensions in addition to the bottom four dimensions.

Solar resource was the most investigated RE resource. Ingenious RE technology applications for solar, wind and hydro ([76,119–121]) were considered. Among the study areas (electrification planning, rural electrification, and renewable energy potential and technologies) investigating these RE resources, 54% focused on a single resource type. 46% focused on different combinations of the available resource types. Given the intermittency prevalent with these resources, it is most expedient to peruse an integrated energy mix in such a way that would compensate for the intermittency amongst these resources.

This review yielded a good foundation that touched on subject areas that are elemental building blocks based on the narrative as contained in literature. There is no recognized integrated framework such that strives harmonize the lessons learned especially at local levels. Therefore, a case can be made for a multi-faceted and more convoluted approach that would harness the interconnections, interdependence, and linkages among these topics. Thus, birthing a holistic integrated framework as depicted in Fig. 10 and expatiated below. The renewable energy potential and technologies track provides an overview of the country's RE resources and reveals the dispersion of these resources across the country. However, there is a need to go beyond these theoretical assessments and inculcate socioeconomic and geographic exclusion criteria [144] to evaluate the viable locational RE potential. This may easily be carried out at disaggregated levels and allows for the adaptation of geospatial approaches for mapping an optimal integrated mix of RE resources on a location by location basis. This information coupled with excerpts from the electrification planning studies would form the foundation for the site identification and selection step. Papers that expounded on energy planning, electrification planning and some rural electrification topics proffered varying levels of energy demand across different locations and application areas. Some incorporated general demand assumptions, others adopted different methods to estimate the demand. This step is crucial for the optimal design and sizing of energy systems. It also facilitates planning, investment, and implementation decisions. Therefore, robust and targeted energy demand is critical especially at disaggregated end-use levels by means of the reference building (RB) approach. This approach would encourage the estimation of energy demand at the location where it is occurring, thus deriving location-based projections while also considering different sectoral scope (Tables 4–6) and corresponding energy access targets. This will avail opportunities for exploring possible energy demand reduction scenarios taking cognizance of the effects of climate change. Since energy demand is not static, the need arises to peruse the evolution of the demand over a long-term period. Also, a comprehensive energy system analysis is needed to explore different technological configurations, their impacts and cost ramifications. These assertions would inform the next step on robust energy demand and supply estimation. This step would support the understanding of possible evolutions of an integrable energy system and enhance sustainable investments in this field with efficient planning and sizing strategies for energy production. Detailed energy system planning, sizing, and design which would draw insights from the previous steps. Studies conducted on policies and reforms, and energy and electricity access impact proffer insights on the prevalent

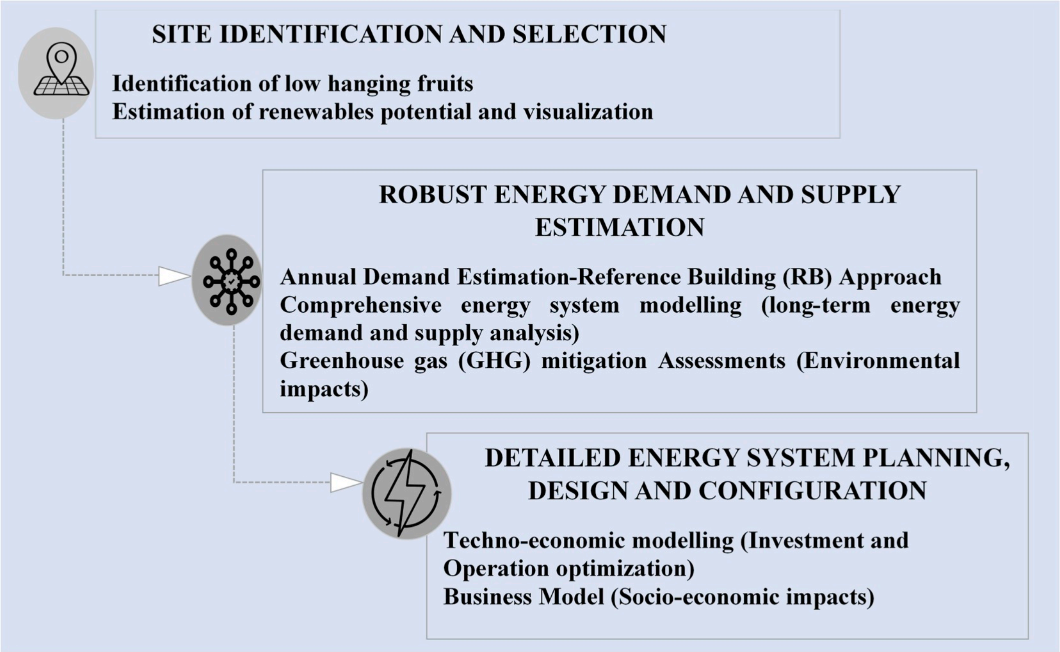

Fig. 10. Proposed scheme of the Integrated Framework for Energy Access Studies.

ecosystems and enabling conditions to foster a sustainable energy system. Viable business models that foster a local supply chain for rural energy solutions would conclude the framework. Overall, this framework would be immensely facilitated by a compendium of methodologies and the application of a multi-tool approach drawing insights from the narrative as contained in literature.

On this premise, further research is been conducted by the authors of this paper. Research efforts are geared towards creating a unified road map for energy planning, system design, and operation with renewable energy integration to improve energy access in rural Nigeria. Given the lack of synergy in terms of strategies and methodology reported, there is an opportunity to co-ordinate efforts and opportunities for collaboration between non-experts and experts in this field.

6. Conclusion

By means of an extensive systematic review of the peer-reviewed literature, the state of the art on the Nigerian energy access studies has been explored. The review topics included energy planning, electrification planning, rural electrification, renewable resource potential and technologies, energy & electricity access impact and policies & reforms. A total of 104 articles, from 1978 to 2019 were discovered from which 90 relevant articles were analyzed. Indeed, several approaches have been adopted in these studies. However, there was no consensus on a standardized framework to synergize the already available strategies and methodologies for improving Nigeria's energy access. Therefore, to capitalize on the interconnections, interdependence, and linkages among these topics, a multi-faceted and more convoluted approach that would proffer an integrated framework is advocated and presented. This would harmonize the lessons learned under the umbrella of a multi-disciplinary study and as such is proposed for future research. It is on this basis further research is been conducted by the authors of this paper. The research aims to conceptualize a unified road map for energy planning, system design, and operation with renewable energy integration geared towards improving energy access in Nigeria. Finally, this review has painted a picture of the narrative regarding Nigerian energy access studies and proposed a new trajectory to peruse for future research.

Declaration of competing interests

The author declares that are no competing interests.

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