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Carbon emissions pinch analysis (CEPA) for energy sector planning in Nigeria
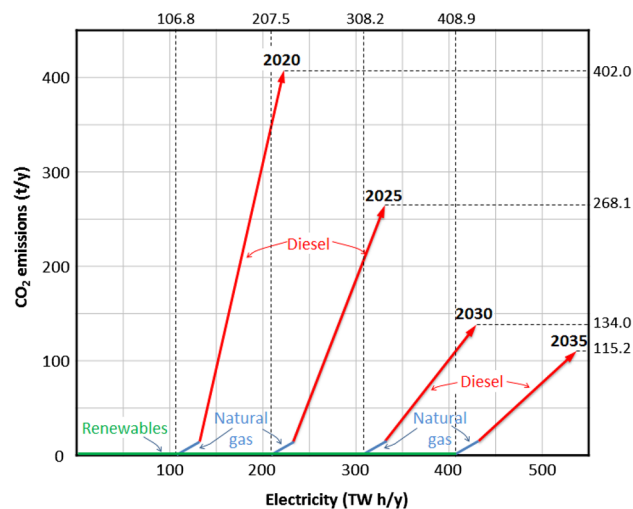
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Abstract

Nigeria has abundant of fossils and renewable energy resources. However, systematic energy planning techniques are desirable to facilitate the sustainable management of these resources. In this work, carbon emission pinch analysis which incorporates macro-level sectorial electricity planning was applied for Nigeria. The minimum renewable targets were determined, and some of the possibilities of realising meaningful emissions reduction with increases in demand were revealed. The minimum renewable target of 408 TW h is required to keep emissions level as that of year 2015, while at the same time meeting the projected demand of 530 TW h in 2035. The present estimation shows that renewable energy applications could immensely contribute to the energy mix and favourable over fossil fuel for carbon emissions reductions. Biomass has the potential to sustain the nation from energy shortages, decrease the grid emission factor for Nigeria electricity sector from 0.91 t CO_2/ TW h (2015) to 0.21 t CO_2/TW h (2035). The electricity generation mix for year 2035 is best derived from biomass, solar, and hydropower.

Graphical abstract

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Introduction

A significant global issue regarding climate change and greenhouse gases emission (primarily carbon dioxide—CO_2) is to reduce the reliance on traditional oil and natural gas

to produce electricity (IEA 2015). It is a significant challenge for developing countries such as Nigeria to implement renewable energy that is technically and economically viable, at the same time environmentally, socially and politically sustainable (Cervigni et al. 2013). As a result, governments across the world have set ambitious targets to reduce greenhouse gas (GHG) emissions from electricity generation. This leads to the development of renewable technologies to harness the energy. These renewable energies such as solar, wind, biomass and tidal wave, however, cannot act as a direct replacement for conventional coal and gas-fired power stations, as there is limited control over their continually fluctuating variable power output (Qiang et al. 2017).

The Global Energy Architecture Performance Index in 2015 ranked Nigeria at 116 among 125 countries in the world. This implies that in the context of electricity, Nigeria is one of the lowest per capita consumers in the world. The nation's highest ever peak generated was 5.1×10^{-3} TW on 2 February 2016 (The Federal Ministry of Power 2016). However, the Ministry of Power put forward a demand forecast at 12.8×10^{-3} TW in 2015. This reflects that the supply predicament which indeed has kept the industrial and socio-economic growths below the potential of the economy (Saifuddin et al. 2016). This chronic deficit has led to the widespread use of self-generation mode (Todd and Gailyn 2017) consequently, making Nigeria the world's largest importer of diesel fuel generators (gen-sets) (Research and Markets 2016). This scenario causes more impoverished environmental impacts, as well as an increase in the price of goods and services. This creates a significant overhead cost onto consumers (Olotu et al. 2015). Furthermore, the CO_2 emission factor of diesel is reported as 2.7 kg CO_2/L (Wright et al. 2011). The lack of reliable energy supply has also left the rural population socially backward since electricity is required for the basic developmental of services such as clean pipe water, healthcare, telecommunications, and quality education (Monyei et al. 2017). Therefore, with such predicaments in mind, the government embarked on deregulation of the electricity sector. However, the underlining question that arises now is whether the market reform initiatives (Saifuddin et al. 2016) can meet up to the expectations of using a sustainable approach. Therefore, GHG emissions must be taken into consideration when evaluating fuel mix for electricity generation schemes in the future. It is paramount that Nigeria would have to establish a clear environmental and economic justification for its electricity generation mix. There is also no reliable estimate for the carbon savings of renewable power in Nigeria. Carbon savings arise due to renewable power displacing other types of generation, but the actual savings (or emissions displacement) will depend upon the mix of generation that they replace.

In fact, Process Integration (PI) was among the optimisation techniques that intrigued the industrial sector during the 1970s oil shock (Klemeš and Kravanja 2013). PI may be defined as the systematic and general methods for designing integrated production systems ranging from individual processes to entire sites, with particular emphasis on the efficient use of energy and reducing environmental effects (Klemeš 2013). PI methodologies such as *pinch analysis* or mathematical programming have been successful in providing answers and support for essential economic development, better utilisation and savings schemes vis-à-vis energy (Linnhoff et al. 1982), water (Foo 2012), and other resources (El-Halwagi 2011). In the last decade, an important extension of PI for carbon emission reduction known as *Carbon Emissions Pinch Analysis* (CEPA) was first introduced by Tan and Foo (2007), where the graphical technique was used to determine the minimum controversial renewable energy resources. However, the main limitation of the work lies in the assumption that the renewable energy has zero-carbon intensity. This limitation is relaxed in their later work (Lee et al. 2009), where the improved graphical technique was introduced to determine the minimum renewable energy with low carbon intensity was targeted. Another class of CEPA problem known as *segregated targeting* was also introduced and addressed using an optimisation framework (Lee et al. 2009), and later by Bandyopadhyay et al. (2010). It has since been applied to different regions. In Ireland, CEPA was used for planning the power regeneration sector (Crilly and Zhelev 2008). Similarly, across Oceania, CEPA was utilised for long-term planning with increasing demand for New Zealand (NZ) electricity industry (Walmsley et al. 2014b). The findings opened up to the feasibility of achieving 90% renewable target by 2025 (Atkins et al. 2010). Similarly, in another work, CEPA was integrated with *Energy Return on Investment* (EROI) to investigate the feasibility of New Zealand attaining and maintaining renewables electricity target above 90% in 2050. The study covered two scenarios: electricity generation increases at 1.5% per annum and 50% switch to electric vehicle transportation for personal use vehicles. The authors concluded that electricity demand is anticipated to reach a maximum ranging between 70 and 75 TW h by 2050 with RE sources to comprise nearly 95% of the electricity generation mix. Overall, it demonstrates an attractive standing economically and environmentally for NZ to sustainably meet future electricity demands (Walmsley et al. 2014a). In another work, researchers extended the work into multi-dimensional pinch analysis (MDPA) to analyse five key indices (EROI, risks, carbon, water and land footprints) for China's power generation sector (Jia et al. 2016). The prospects of achieving 33% renewable electricity generation planning were reported for the state of California, America (Walmsley et al. 2015). A comprehensive review of process integration techniques has been reported by Foo and Tan (2016).

The commitment towards sustainable development is stable even for countries endowed with vast reserves of fossil hydrocarbons. The United Arab Emirate's energy mix policy targets the share of natural gas be reduced from 98 to 76% by 2021 and further down to 38% by 2050 (Lim et al. 2018). Therefore Lim et al. (2018) analysed the electricity sector using CEPA to examine the 2050 target focusing on the climate-energy-water nexus. By constraining the carbon emissions to the 2012 levels, with maximum EROI and minimum water footprint, the electricity sector in year 2050 is to be dominated by renewable energy, particularly solar power. Saifuddin and Bello (2017) studied the post-liberalisation era (2013–2015) of the Nigerian electricity sector, the authors concluded that the country's gen-set market would continue to soar and dominate the largest share of the generation mix. To this effect, CEPA application was extended for the first time to an African country, to examine the consequential effects of greenhouse gas emissions from using fossil fuels. Nevertheless, the approach using CEPA technique was at a preliminary level to ascertain the corresponding CO_2 emissions from the existing national generation mix.

Furthermore, there are limited studies for tracking the growing use of fossil diesel in the existing gen-sets market for the Nigerian environment. Hence, this presents some unique features on which this study hinges. This paper also leverages bioenergy potential from lignocellulosic biomass with constrained environmental factors. The objectives of this paper are to apply the CEPA approach to the systematic planning of power generation sector in Nigeria, considering on- and off-grid generations. Besides, it is aimed to determine the minimum amount of renewable energy, with emphasis on lignocellulosic biomass, required to keep carbon emissions within the year 2015 level. In essence, this paper extended the analysis for the work of Saifuddin and Bello (2017), by incorporating time-based analysis, in which CO_2 emission targets are to be met subsequently with time interval planning.

Methodology

A correlational research approach is employed for this study. First, CEPA is used to determine the relationship between the various fuel sources of electricity and their corresponding CO_2 emissions levels. The best way to start is with a philosophical orientation on the structure of the Nigerian electricity generation system. The system is broadly categorised into transmission-based *on-grid* and *off-grid* generation. The on-grid is a strictly hierarchical system with clear demarcations between its generation, transmission and distribution subsystems (Farhangi 2010). The Nigeria Electricity Regulatory Commission (NERC) regulates this system.

Hence, the data totalling 30.8 TW h for year 2015 for power plants (hydropower and natural gas) are obtained from the NERC (NERC 2016).

On the other hand, the other generation can be further classified into three sub-classes namely *captive*, *off-grid* and *embedded generation*. On one hand, captive generation refers to a system in which the generator consumes entirely by itself and does not require any evacuation through the grid transmission nor the distribution network. Off-grid generation, on the other hand, requires external off-takers (distribution network only). The embedded generation is the case where embedded generators are connected to the distribution network for evacuation to the specific customer load. A common characteristic of these three forms of generation is that the installed capacity is averagely below the regulatory standards. Therefore, statistical data is not available from NERC, and so, the off-grid energy facts are based on estimation reported elsewhere (NESP 2015). These are considered the most stable sources of energy facts available in the literature of the Nigerian electricity sector.

The graphical CEPA technique (Tan and Foo 2007) adheres to the principles of the *energy planning pinch diagram* (EPPD, Fig. 1). The diagram consists of the electricity demand and source composite curves, in which it consists of individual segments that represent the demands and sources arranged in ascending order of emission factors (EFs). The latter corresponds to the intensity of emissions produced per unit of electricity, which is represented by the slope of the individual segments of the composite curves. For a feasible pinch diagram, the source composite curve must stay to the right and below the sink composite curve, with the composite curves touching each other at the *pinch* point (see Fig. 1). The horizontal opening on the left corresponds to the minimum amount of renewable energy required to satisfy the
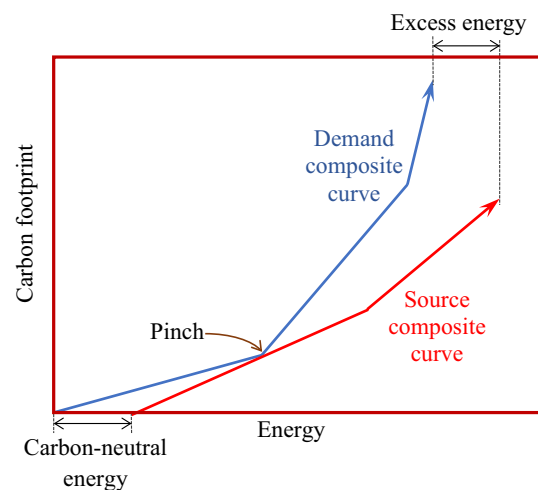

Fig. 1 Energy planning pinch diagram (EPPD)

system's specified emissions limits, while that on the right is the excess fuel sources that cannot be used due to the emissions limits. Further details on the construction of composite curves are covered elsewhere (Foo and Tan 2016).

Based on the targeted results of CEPA, the renewable energy target will be evaluated, to ensure that the target is achievable. In the case of Nigeria, the renewable energy target is to be fulfilled by its biomass material. The potential electricity for the biomass resource can be calculated using Eq. (1), adapted from Li et al. (2016) to check if the amount of cultivated biomass from oil palm is enough to meet the targets.

$$E^P = Q_M \times \beta \times \text{HHV} \times \mu/3600 \tag{1}$$

where E^P is the potential energy from advanced fuel in GW h/y; Q_M is the quantity of biomass in t/y; β is the collection efficiency; HHV is the higher heating value for biomass GJ/t; μ is the theoretical liquid yield obtained from pyrolysis.

CEPA for Nigerian power generation sector

As Nigeria continues to struggle through its electricity generation schemes, there is a need to incorporate the planning of energy sources at the early stages of decision making to meet the energy demand within acceptable carbon emission constraints. The emerging section includes a scenario for 2015 (current state of the generation), a predicted scenario for 2035 (future outlook) and some strategies for emissions reduction.

Scenario for 2015

Table 1 contains the 2015 electricity and emission data utilised in applying the CEPA methodology for Nigerian electricity generation system. The EFs for natural gas (NG) and diesel fuel, as well as the sectorial demand data for Nigerian electricity consumption, were obtained elsewhere (NESP 2015). The table reveals that the residential sector consumes the most energy generated, and it contradicts with other countries. The first explanation for this is that the commercial sector has since collapsed as they could no longer bear the excessive cost of running backup generators (Alley et al. 2016). Similarly, the total on-grid electricity supplies, based on generation portfolio in 2015, are 20:80 for hydropower (HP) and natural gas respectively (NERC 2016). The estimated off-grid electricity between 70.1 and 122.6 TW h of capacity is suggested to be generated from the decentralised diesel generator (NESP 2015). From these, the mean value (96.4 TW h) was considered in this study for the total off-grid electricity supply.

The EPPD is plotted for the Nigerian electricity generation system based on the 2015 data for the chosen base year (2015), as shown in Fig. 2. The Nigerian total (on-grid and off-grid) electricity consumption and the corresponding carbon emissions stand at 127.2 TW h and 115.3 t CO_2 respectively. For the on-grid generation, the fuel mix in 2015 is predominantly comprised of natural gas (24.7 TW h, or 80%) and hydropower (20%). Hence, the latter accounts for the existing portfolio of carbon–neutral fuels of 6.1 TW h. It is worthy of note that the *grid emission factor* (GEF, for the entire demand sector) can be assumed to be proportionate to the electricity usage. Therefore the calculated GEF in 2015 is 0.91 t CO_2/TW h.

Table 1 Electricity and emission's data for Nigeria in 2015

| Demand				
Sector	%Distribution	Quantity (TW h)	Emissions factor (t CO_2/TW h)	Emissions (t CO_2)
Residential	57.8	73.5	1	73.5
Industry	15.8	20.1	1	20.1
Commerce & others	26.3	33.6	1	33.6
Total demand	100	127.2		127.2
Supply				
Generation	Fuel source	Quantity (TW h)	Emissions factor (t CO_2/TW h)	Emissions (t CO_2)
On-grid transmission based	Hydro	6.1	0	0
	Natural gas	24.7	0.553	13.7
Off-grid; embedded & captive	Diesel	96.4	1.054	101.6
Total supply		127.2		115.3
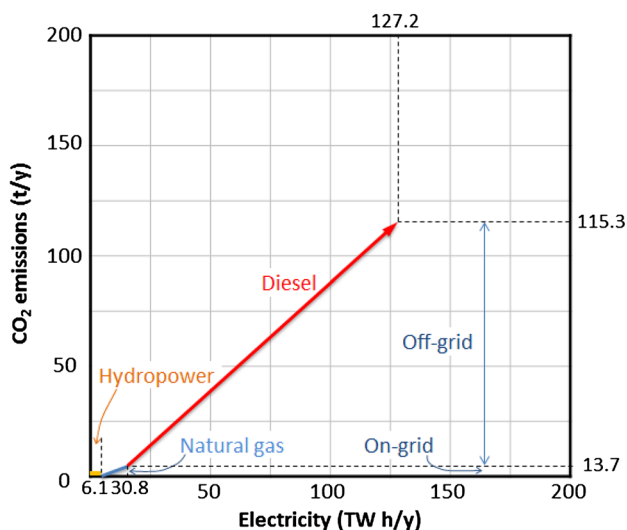
Fig. 2 EPPD for year 2015

The emission factor for diesel fuel reported in the literature is highly specific to engine technology and location. An individually-owned 5 kW diesel generator emits two times as much as larger gen-sets, which are even more expensive and far less frequent, only cost a little better than coal. Equally, a coal power plant, usually considered the worst energy option for the environment, might produce $\sim 1.0 \times 10^{-6}$ t CO_2/TW h. For example, the carbon emission coefficient of the coal-to-energy plant in China was studied to be around 0.875 t/TW h (Yu et al. 2014). According to the study, this is relatively low as compared with that of other countries (Yu et al. 2014). In this case, the EF for the diesel fuel combusted in gen-set may range from 1.580 to 0.699×10^{-6} Mg/TW h (Moss and Gleave 2014). For this study, due to the limitation of data covering individual types of generators in operation, the average emissions factor is taken.

Similarly, emissions factors for the natural gas generation were taken as 0.553 t CO_2/TW h (Moss and Gleave 2014). According to a lifecycle approach, all renewable generation sources will have emissions factors due to total supply chain management. However, even though their life cycle estimates are typically at least one to two orders of magnitude lower than fossil fuel-based thermal generation, in this analysis the life cycle emissions are ignored and assumed to be zero for hydropower. In Fig. 2, It is noteworthy that the transmission-based on-grid system only supplies 24%, which is equivalent to 30.8 TW h ($= 24.7 + 6.1$ TW h) of the total electricity from natural gas and hydropower. Concerning emissions, on-grid system accounts for almost 12% of carbon emissions (13.7 t/y) of the total electricity sector. This could translate that the balance (101.6 TW h; 76%) is provided by fossil fuel powered gen-sets (off-grid generation), which is responsible for 88% of the overall carbon footprint of the power sector. This is reflected by the EPPD in Fig. 2.

In the previous work of the authors (Saifuddin et al. 2016), the developmental status of electricity in Nigeria was reviewed. Also, the challenges of preventing the progress of accessible electricity was examined. The current status quo requires a new approach to the power generation scheme in Nigeria, with procedures to impede the growing threats of CO_2 emissions from gen-sets. In this context, alternative energy generation from local biomass, mainly lignocellulosic, could be one of the most viable solutions to rapidly minimise the intake of fossil fuels, to reduce environmental and energy complications. Keeping in view the whole problems, Table 2 shows population, centralised grid electricity data for the MINT(S) countries—Mexico, Indonesia, Nigeria and Turkey in 2009, 2014 and beyond. The MINT(S) countries are regarded as new emerging economic giants (Asongu 2016). South Africa is Nigeria's peer economic advancement in the continent. Thus, it has been included in Table 2 for continental comparison. The table also shows the associated emissions from the MINT(S) countries, collected through CARMA (Carma 2015) and World Bank (The World Bank Group 2017). The CARMA database (Carma 2015) captures future developments that companies and plant builders have divulged. Hence, in some cases, the reported plans may be concrete and comprehensive, but they may also be tentative and incomplete for others, especially those beyond 2009. A good example is the Gurara 30 MW hydropower in Kaduna province, Nigeria. The project was awarded in 2009 with planned completion after 36 months. However, the project is yet to be completed to date. This illustrates the unfortunate characteristics of infrastructural development that has led to the present dearth in electrifying the nation. In Table 2, the percentages of hydropower (*H*), nuclear (*N*) and renewables (RE) are summed up and categorised as carbon–neutral fuels. Overall, it is evident that the emissions grow with increasing supplies of electricity and an upsurge in population and accessibility. Remarkably from Table 2, it is shown that in 2014 Nigeria has the lowest population with access to electricity, i.e. 57.7% of its population, leaving behind 77 million of the populace without connection to electricity. To bring to the fore, this figure represents the total population of the Republic of Turkey. In other words, this may imply that Nigeria has the capacity of doubling its electricity market size concerning accessibility, unlike any of the MINT(S) peer countries. Though, accessibility to electricity has only grown by 2.1% in the last decade as could be viewed, in Table 2. A point worthy of note, this does not factor in the rapid increases in the nation's population. Table 2 also shows that the power generation in Nigeria is only 13% as what was generated by the second lowest among the MINT(S) countries, i.e. Indonesia for both 2009 (18.39 vs. 139.1 TW h) and 2014 (30.4 vs. 228.6 TW h). This confirms with literature that Nigeria's electricity sector still struggles with multifaceted challenges (Alley et al. 2016). It needs to be

Table 2 Population, electricity, and emissions for the MINTS countries (Carma 2015; The World Bank Group 2017)

Country	Population (000)	Year	Electricity access (%Pop.)	Generation (TW h)	Emission level (t CO$_2$)	Carbon–Neutral fuel Mix (%)			
						H	N	RE	Total
Mexico	127,017.22	2009	99.1	234.15	117.81	11.3	4.3	3.0	18.6
		2014	99.2	301.5	–	12.9	3.2	4.6	20.7
		Future*	–	344.72	161.84	8.4	9.3	4.2	21.9
Indonesia	257,563.82	2009	96.0	139.10	110.89	8.0	0	6.3	14.3
		2014	97.0	228.6	–	6.6	0.0	4.8	11.4
		Future*	–	433.74	377.86	5.0	2.9	6.1	14.0
Nigeria	182,201.96	2009	55.6	18.39	8.31	24.3	0.0	0.0	24.3
		2014	57.7	30.4	–	17.6	0.0	0.0	17.6
		Future*	–	67.07	37.25	22.7	0.0	0.1	22.8
Turkey	78,665.83	2009	100.0	182.47	96.61	19.5	0.0	0.9	20.4
		2014	100.0	252	–	16.1	0.0	4.8	20.9
		Future*	–	498.63	246.93	19.0	6.2	3.3	28.5
South Africa	54,956.92	2009	85.4	235.60	224.93	0.6	4.9	0.1	5.6
		2014	86	249.5	–	0.4	5.5	1.0	6.9
		Future*	–	348.86	292.76	0.8	9.2	2.3	12.3

*This indicates forecast for the years beyond 2020

resuscitated from an acute energy deficit while keeping the pace of population growth and sustainable development (Oyedepo 2012). Under the current trajectory in Table 2, Nigeria is to experience growth of 264% (i.e. from 18.39 to 67.07 TW h) in power generation in the future from the year 2009. This will come along with a corresponding emissions growth of 348%, assuming that the fuel mix remains identical. Note that Nigeria has the highest power generation using hydropower sources (24.3% in 2009 and 17.6% in 2014), yet, negligible in other renewable sources. The results are reasonably in agreement with the results of Table 1. In addition, there has been a 6.7% decline from hydropower generation between 2009 and 2014. Moreover, future data projections (Table 2) in the use of carbon–neutral fuels depict that there will be a 120% increment for South Africa and 40% for Turkey; whereas, for Nigeria, carbon–neutral fuels utilisation will decrease at the rate of 6%.

The electricity sector in Nigeria has experienced consistently rapid growth in demand. However, a reverse growth of the central grid and lack of its accessibility has led to the exponential increase in net emissions. The national grid had an installed capacity of 6500 MW but handled a wheeling capacity of maximum 4500 MW. The nation recorded its highest grid generation of 4716 MW on February 07, 2016 (Saifuddin et al. 2016). According to Onochie et al. (2015) Nigeria needs a minimum growth in its electricity generation strength by 7% exclusive of the deficit, to attain a sustainable economy and reach its full potentials. However, from the results in Table 2, this is far from happening anytime sooner. The underperformance of the power plants has caused an acute shortage of electricity in Nigeria with power

outages of several hours per day. Somehow, this shortfall had to be realised and has resulted in the over-reliance on off-grid electric power generation. An estimation between 8 and 14 GW of decentralised diesel generator capacity is currently installed in Nigeria, more than 86% of the businesses in Nigeria own or share a generator (NESP 2015). Therefore, this validates the demonstrations that the vast backlog has been satisfied predominantly by fossil fuel-based gen-sets.

Scenario for 2035

Considering the poor performance of the power generation, the Federal Government of Nigeria (FGN) embarked on full deregulation of the power sector. On 1st November 2013, the FGN unveiled a milestone in its electricity market reform with the relinquishment of properties to the 6:11 series of new entrants, i.e. six generation and eleven distribution companies, while the transmission has remained with the government. Salman and Neshaeimoghaddam (2017) attempted to analyse the Nigeria electricity generation during the post-deregulation period (2013–2015). The authors reported that there has been only around 0.56% additional capacity made onto the central grid in Nigeria. As such, they concluded that energy supplies in Nigeria would continue to be dominant by diesel-based gen-sets, in the absence of other energy resources.

In another study that modelled the Nigeria energy demand and supply projections covering 2005–2030, Sambo (2008) concluded that a significant investment in the tune of US$ 484.62 billion would be needed for additional electricity generation capacity to meet the optimistic growth

scenario of 0.298 TW in 2030. This was based on 13% GDP growth which the government desires to meet its ambition of becoming among the world's first 20 economies by 2020 (Sambo 2008). Similarly, the World Bank forecasted that the demand for electricity would continue to grow at 7.4% to reach 530 TW h in 2035 (Cervigni et al. 2015). However, it is a concern that with current growth trajectories, these would only be met with decentralised gen-sets. Therefore, it will result in an increasing trend to higher GEF over the same period. The total electricity demand and emissions for Nigeria in 2035 were forecasted 530 TW h and 536.5 t CO_2/TW h respectively (see EPPD in Fig. 3; Table 5 for data). Hence, the GEF may be calculated as 1.01 t CO_2/TW h (= 536.5 t CO_2/530 TW h). Emissions from the electricity sector in 2035 are shown to increase exponentially by approximately fivefold (as compared to that of 2015), due to the excessive use of diesel. Figure 3 also shows that off-grid generation using diesel-powered gen-sets will constitute up to 521 t CO_2 (97%) of the total emissions, while the on-grid generation is contributed by natural gas for as little as 15.5 t/y CO_2 (2.9%). These emission levels will have significant implications for the national environments and pose severe and costly risks to public health (Mittal et al. 2016).

Furthermore, the trend of increasing emissions is expected to continue growing from 2019 as there have been fluctuations and shortages in the supply of automotive gas oil (diesel) and low pour fuel oil (black oil) in the past. This is due to the Dangote oil refinery facility that is still in the construction stage (Ezeocha 2016). Upon the successful completion of the 650,000 barrels per day capacity refinery, diesel supply shortage will considerably be reduced. Thus, emissions from 2019 are expected to soar and possibly exceed the 2035 forecast levels. It can be observed that Nigeria consumed 200, 180, 150 billion litres of diesel and black oil in 2012, 2013 and 2014 respectively (Salman

Fig. 3 EPPD for year 2035

and Neshaeimoghaddam 2017). Note that according to the state-owned oil corporation, Nigerian National Petroleum Corporation (NNPC) through which the federal government of Nigeria partakes and regulates the republic's petroleum industry, these figures are incomplete because some independent marketers were yet to submit their records as at the time of preparing the reports (NNPC 2015). Population growth is a determinant factor that complements the demand for electricity. Nigeria is also acknowledged as the giant of Africa because it has the largest population in the continent of over 170 million in 2015 and forecasted at 310 million in 2035. According to the UN population division, the future increases in the world urban population are expected to be highly condensed in just a few countries. Nigeria is expected to account for about 37% of the increase of nearly 2.5 billion people in the urban population by 2050 (DESA 2015). Similarly, at present, the most significant rural populations in Africa are located in Nigeria (95 million), from the year 2014 through to 2050, it is expected to register the most massive increase of 50 million (Bongaarts 2014). All these have made it paramount to increasingly promote the utilisation of the vast renewable energy resources to accelerate development.

However, it is worthy to recall that Nigeria holds one of the most abundant fossil energy resources on the continent, including natural gas reserves (166 trillion standard cubic feet) and crude oil (36 billion barrels) (BP 2015). Additional energy resource includes coal and lignite (2.7 billion tonnes) (Ohimain 2014). Since the country faced with severe energy shortages, the adoption of renewable energy comes with some risks of reduced availability and reliability Inevitably, it is fair that baseload electricity generation will still rely on fossil fuels. Furthermore, it is considered infeasible to discontinue building and operations of the existing fossil fuel-based plants and gen-sets when the economic lives are not fully expended unless taken into account the external cost of greenhouse gas emissions (Lim et al. 2018). Therefore, the natural gas portion in the generation mix was assumed to remain constant in this study. As a result, the country can consider an increase of carbon–neutral energy sources discussed above. Also, Carbon Capture and Storage (CCS) retrofits in either existing or future gas or coal power plants will be necessary to reduce CO_2 emissions from such plants for managing global climate change. At the moment, the concept of CCS is considered as the only option that permits the conventional power generation technologies to continue in either operation or construction without excessive contribution to global warming. Thus, since most of the existing independent power plants in the country are using combined cycle gas turbines, retrofitting these plants with CCS is desirable in order to reduce their carbon emission level (Markovska et al. 2016). The deployment of CCS technology applications can be seen as one of the alternative
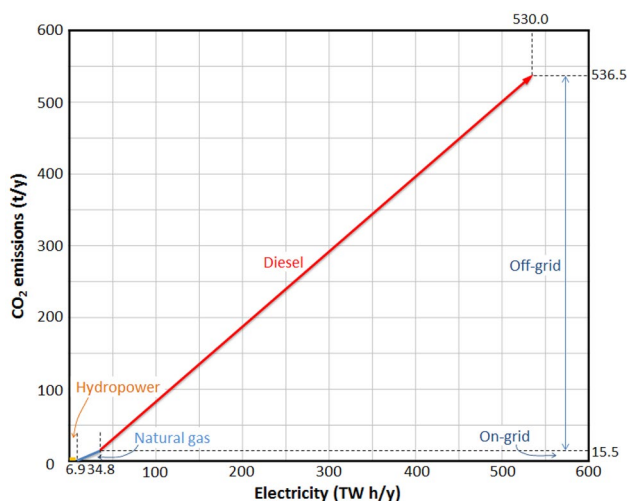
solutions during the interim period of transition from fossil-based to the low carbon energy system (Markovska et al. 2016). Examples of the case study can be observed from the UAE. The UAE has set critical lessons for Nigeria and other developing countries to follow by its first commercial-scale carbon capture use and storage (CCS) facility in the Middle East. The plant can sequester up to 800,000 t of CO_2 per annum from its carbon-intensive steel industry, the captured CO_2 will be used to enhance oil recovery regarding saving natural gas and environmental return (Lim et al. 2018).

Strategies for emission reduction

It is now widely accepted that a high level of renewables for electricity generation is a vital strategy in reducing GHG emissions and creating a sustainable world. This will be a realistic aspiration for carbon reduction goals in Nigeria. However, supply security through a well-balanced energy mix for a given constrained carbon emission in short to medium term is worth some scientific investigations. Therefore, this section aims to identify electricity targets from carbon–neutral sources needed for mitigating the forecasted 2035 emissions to 2015 levels.

The EPPD in Fig. 2 shows that the electricity consumption stood at about 127.2 TW h for 2015, with total carbon emissions of 115.3 t CO_2. Admittedly in Fig. 3 electricity demand and corresponding emissions will increase to 530 TW h and 536.5 t CO_2 by 2035. This is based on the assumption made from 2015 through 2035; the electricity will grow in demand by 7% while predominantly satisfied by diesel gen-set generation modes. Moreover, because there is currently no baseline benchmark for the Nigeria electricity sector carbon emissions, the EPPD in Fig. 4 shows the proposed strategy in this work, i.e. to reduce the emission to the same levels as in 2015, while instantaneously meeting the increased demand by 2035. In this case, the energy demand for years 2020, 2025, 2030 and 2035 are predicted as 227.9, 328.6, 429.3, 530 TW h respectively (estimated based on yearly average), while their corresponding CO_2 emission is determined as 402.0, 268.1, 134, 115.2 t/y, individually. For the latter figures, they were assumed to be based at 25% in 2020, 50% in 2025, 75% in 2030 and 100% in 2035 (i.e. achieving the carbon emissions as of year 2015). In other words, the GEF is to be reduced to 0.21 t CO_2/TW h (=115.2 t CO_2/530 TW h) in year 2035, as compared to its initial value of 1.01 t CO_2/TW h (see discussion in previous section). The five-year planning cycle is due to the fact that the implementation of 100% renewable energy could not be possible in the short term for reasons such as political will, reviving the agricultural sector for the collection of more biomass. Hence, the percentage of implementation strategies are considered while the procedure for performing CEPA is the same for all strategies. The application of carbon–neutral
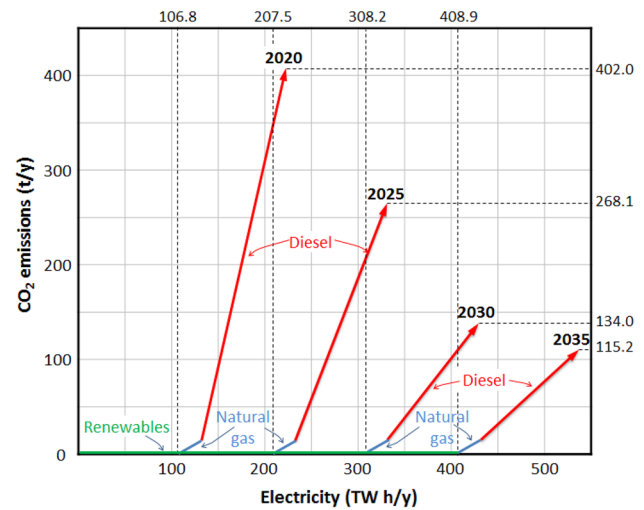

Fig. 4 EPPD for different years of planning

energy resources is expected to lower the GEF from 0.91 t CO_2/TW h in 2015 and 1.01 t CO_2/TW h under the business as usual scenario in 2035, to as low as 0.21 t CO_2/TW h in 2035 of beatnik generation.

The EPPD in Fig. 4 indicates that the carbon–neutral fuel corresponds to 106.8, 207.5, 308.2 and 408.9 TW h for years 2020, 2025, 2030 and 2035 respectively (Fig. 4; see details in Table 6 in Appendix). This procedure identifies the electricity mix needed to meet both the energy demand and emissions limit simultaneously. The advantage would be that it practically takes into consideration the time required for legislation, planning, and the construction and commissioning of new renewable power plants. Besides, this would also require the introduction or modification of new policies and a gradual diversification of investment to build new renewable generation capacity.

Table 2 indicates that carbon–neutral fuels in Nigeria has a negative future growth (beyond year 2014) in the context of electricity fuel mix. Interestingly, recent work (NESP 2015) has pointed to the exploration of the country's renewable sources exemplified in Table 8 and how these resources could potentially facilitate in closing the energy supply deficits and action points towards building sustainable societies.

Table 8 shows that Nigeria has some potentials for realising these targets. However, for realistic development, there is a need to confirm if the available resources are indeed capable of satisfying these targets. Worthy to note that, Nigeria is locationed within latitudes 4° and 14°N, which is an ideal location that is endowed with intermediate solar radiations at a reasonable level of *direct normal irradiance* (DNI). In the northern region, for example, DNI varies from 2.0–2.8 × 10⁻⁹ TW h/m²/day (Ogunmodimu 2012). Muhammad (2012) in his study confirms that northern parts of Nigeria recorded an average value of 2.2 × 10⁻⁹ TW h/

m^2 of DNI per annum. Another study by Ogunmodimu and Okoroigwe (2018) reviewed that if only 1% of the DNI area is being utilised at a capacity factor of 40%, about 181 TW h/y of solar energy could be produced. The potential from hydropower is determined by increasing the threshold of the current utilised capacity (for all small and large power plants) to full potentials (NESP 2015). Energy production from wind harvesting, the annual wind speed ranges across the states. For example, the annual wind speed recorded was 3.89 m/s for Sokoto and 2.32 m/s for Port Harcourt (Brimmo et al. 2017). Energy realisable from wind turbine having an efficiency of 30% is about 97.0 in the northern state of Sokoto and 25.7×10^{-6} TW/y in southern Lagos state. The prospects for nuclear energy have seen some attention as an alternative form to the electricity supplies. However, no nuclear power plants are currently under construction in the country.

Apropos energy tradition, the European committee for standardisation published two standards for classification and specification (EN 14961) and quality assurance (EN 15234) of biomass. Loosely, biomass may be classified into two broad groups, namely virgin biomass which includes lignocellulose (wood, plants, and leaves) and carbohydrates (crops and vegetables). The second class of biomass type is the waste biomass comprises of municipal solid waste (MSW) (solid and liquid wastes) sewage, animal, and human wastes (Basu 2013). Population size, growth pattern and distinctive demography label Africa to home a quarter of the world's population by 2050 and most massive working age by 2040 (DESA 2015). Even more interesting, per capita income is coming to an inflexion point where a high enough per capita level is reached that consumer demand takes off in addition to, there has been 10% increase in life expectancy since 2000–2010 (Verghese 2015). Furthermore, there are 72 cities in the continent of Africa with more than one million population and urbanising at 0.3% compared to China's 1.0%; the urban population will typically consume more per capita than the rural one (Verghese 2015). That being the case, there will be a substantial increase in agricultural products and correspondent wastes (virgin and waste) as the Africans middle class grows to be tomorrow's producers and consumers. The African giant (Nigeria) can strategically play a significant role in satisfying both the demand and supply sides of the equation by leveraging on its potentials. Nigeria is estimated to generate about 25 million tonnes of municipal solid waste annually based on a study (Ogwueleka 2009). Similarly, it has also been estimated that Nigeria produces about 227,500 t of fresh animal waste daily which is sufficient to generate between 12.4 and 17.4 TW h of electricity year on year (Ben-Iwo et al. 2016). With the exemplary of Lagos state waste management authority, this area has recently been gaining political will from some state governments. Another technical information (Somorin et al.

2017) reported that the annual electricity generation potential from MSW was estimated to be 26.7 TW h/y and the detail of the study is shown in Table 8. These are immense potentials and opportunities for leaping large-scale reliance on utility-scale renewable power plants.

On the side of virgin biomass, bioenergy transfigration technologies are used for converting biomass into useful energy. These technologies are mainly either at developmental or implementation stages for transforming biomass into energy and value-added products. For instance, lignocellulosic biomass is mainly composed of cellulose (23–60%), hemicellulose (25–44%), and lignin (12–49%) (Du et al. 2013). Generally, cellulose and hemicellulose result in more bio-oil than lignin. However, some other biomass types, such as oil palm shell may have high lignin contents (45–48 wt%) compared to other biomass. The rich lignin found in oil palm shell could be a good source of renewable phenol and phenolic chemical compounds (Stefanidis et al. 2014). Thus, if these endowed resources are underutilised, both energy and value-added products cannot be produced. Nomanbhay et al. (2017) reviewed the use of pyrolysis technology as an efficient thermo-chemical process for energy applications, to replace fossil fuel in an existing gen-set system, or to generate electricity using a gas engine using industrial and non-industrial derived biomass residues (with a specific example of solid palm oil residues in Nigeria). An estimated power generation potential of about 500 MW can be obtained using only the available residues from oil palm industry in Nigeria. Furthermore, the potential can be increased tenfold with more emphasis on expansion and modernisation of oil palm industry in Nigeria (Nomanbhay et al. 2017). This will provide benefits such as renewable power generation, higher revenue from the palm oil export, as well as tackle the growing youth unemployment.

Nigeria has about 24 million hectares of land that is suitable for oil palm cultivation across fifteen of its thirty-six states (Dada 2007). The recent contraction of the global economy amid fluctuations in oil markets has spurred commitment by the FGN to improve non-oil export and sectors as part of measures to sustain the economy. Researchers such as Saifuddin et al. (2016) have advocated Nigeria to reclaim the palm oil industry to crucial economic drivers of the agricultural sector. Another advantage is palm oil generates a considerable quantity of residues that can be processed to produce biofuel. The extracted oil constitutes only 10% of the total biomass generated while the other 90% considered as wastes (Abdullah and Sulaiman 2013). On average, a total of 50–70 t of biomass residues are produced per hectare of the plantation (Abdullah and Sulaiman 2013). These waste by-products reproduced through palm oil extraction are oil palm trunk, frond, empty fruit bunch, mesocarp fruit fibre, kernel shells, and mill effluent (Abdullah and Sulaiman 2013). Hence, four stratagems with different collection

efficiencies are considered, i.e., low collection rate at 20% by 2020, medium collection rate at 40% for 2025, high collection rate at 70% in 2030 and excellent collection rate at 100% in 2035. Nevertheless, this study limits its scope to the use of virgin (lignocellulosic) biomass (oil palm wastes, other widely grown agricultural waste and energy crops residues) for demonstration due to its widespread abundance and has not yet been explored in Nigeria. Howbeit, other renewable resources were reappraised in the events that biomass was incapable of fulfilling the representative demand.

Stratagem I: low collection efficiency ($\beta = 20\%$; year 2020)

A multitude studies such as Stefanidis et al. (2014) have established that biomass is converted into bio-oil, biochar, and non-condensable gases through pyrolysis. The bio-oil is a renewable liquid product of the pyrolysis of biomass. It can hypothetically be used as a fuel or chemical feedstock. The gas produced from pyrolysis is of high calorific value. It can be used to offset the total energy requirements of the pyrolysis plant and equally used as syngas. Furthermore, the pyrolysis of biomass also produces a solid product, i.e. biochar which may be used in different industries for the production of chemical products, inclusive of as a high-efficiency solid fuel in boilers where biomass is burnt (Abnisa et al. 2013). Though as much as 70 wt% of biomass can be converted to liquid oil via pyrolysis, the yield significantly varies depending on the type of reactor deployed for the thermal conversion process. Consequently, the study recommends that pyrolysis is a valid technique, with an assumption of 30% for plant efficiency for all scenarios under investigation. A conceivable generation mix that could achieve the target reduction in emissions to 2015 levels in 2035 is shown in Table 3. As claimed by Dada (2007), an estimated area of 1.65 million hectares is currently under cultivation in the southern part of Nigeria. Therefore, the total yield of biomass will be 82.5 million t/y (= 50 t × 1.65 million hectares), assuming a minimum of 50 t is generated from each hectare (Abdullah and Sulaiman 2013). The energy potential was calculated based on the total amount of selected waste biomass available in Nigeria. The amount of the debris established at a different collection rate over time to 2035. So, the total quantity of oil palm wastes that can be used

to produce potential electricity is substituted into Eq. (1). However, the collection efficiencies could not be practically possible at 100% in short to medium term, due to cultural resistance to new technologies, the maturity of the project and the willingness to collect biomass, all pose an operational risk on supply security.

In 2015, oil palm production in Nigeria was characterised by poor plantation culture (Saifuddin et al. 2016). This is the basis for the low collection efficiency of 20% for the year 2020. With the average thermal energy of the oil palm biomass of 18.58 GJ/t (Nyakuma et al. 2013), the energy potential from oil palm biomass in year 2020 may be calculated using Eq. (1) as 25.5 TW h/y (= 82,500,000 t/y × 0.2 × 18.58 GJ/t × 0.3/3600 GW h/GJ).

Likewise, a similar procedure is applied to other agricultural residues shown in Table 3 while itemisation of the residue is manifested in Table 7, with the total energy potential calculated as 36.9 TW h/y (= 145,600,000 t/y × 0.2 × 15.23 GJ/t × 0.3/3600 GW h/GJ). Note that the assumption made for average heating value for all other agricultural residues is 15.23 GJ/t (White et al. 2011), though they have different thermal values due to the diverse nature of the biomasses. All other assumptions on the collection and thermal plant efficiency remain identical to that of oil palm biomass.

A similar procedure is repeated to calculate the total energy potentials for the energy crops in Table 3. As calculated previously, all assumptions remained except for the heating value of the energy crop. In this study, Jatropha Curcas with a heating value of 24.0 GJ/t (Jingura et al. 2010) is taken as an example. Table 3 reported that the total land available for energy crop plantation is 28.2 million hectares. However, the currently cultivated land is 8.5 million hectares. It is also assumed that a hectare of Jatropha plantation yields 7 t of seeds per year (Onabanjo and Di Lorenzo 2015). Equation (1) hence calculates that the total energy is that could be generated from energy crops is 23.8 TW h/y (= 59,500,000 t/y × 0.2 × 24.0 GJ/t × 0.3/3600 GW h/GJ). Table 3 shows the summation of the potential energy from the selected biomass components above versus the calculated targets. In 2020 basis, Nigeria can produce about 86.2 TW h of energy by utilising its virgin biomass resources at collection efficiency rate of 20%. As a result, the scenario exemplifies the situation where the biomass is insufficient

Table 3 Potential biomass renewable energy sources in Nigeria (Dada 2007; NESP 2015)

Potential biomass	Utilisation per year	Heating value (HHV), GJ/t	Potential electricity at varying collection rates (TW h/y)			
			20% (2020)	40% (2025)	70% (2030)	100% (2035)
Oil palm residues	1.65 million ha cultivated (82,500,000 t)	18.58	25.5	51.1	89.4	127.7
Agricultural residues	145.6 million tons, 2010	15.23	36.9	73.9	129.3	184.8
Energy crops	8.5 million ha cultivated (59,500,000 t)	24.00	23.8	47.6	83.3	119.0
Total			86.2	172.6	302.0	431.5

to satisfy the target determined by CEPA (106.8 TW h/y), by about 20.6 TW h/y ($=106.8-86.2$). The EPPD is shifted horizontally through 20.6 TW h/y to meet the deficit which target biomass demand could not fulfil for the scenario under investigation. The deficit of electricity would need to be supplemented by other forms of carbon–neutral fuels, such as hydropower or solar energy. Although, it is a promising technology to harness and convert the solar energy to electric power, its application in Nigeria is just gaining ground. Hence the integration of hydropower is preferred. Therefore, it is important to determine the outsourced electricity from hydropower to match the obtained target of CEPA. Evidently, from Table 8, we observe that the hydropower fraction can be further bolstered upon on a yearly basis. Nigeria can produce about 28 TW h/y of the total carbon–neutral electricity target. Thus, the scenario was set up based on the assumption that the hydropower capacity is underutilised. The optimal electricity mix is shown in Fig. 5, which illustrates that the new target of electricity from carbon–neutral biomass is identified as 86.2 TW h/y, translating to 80.7% of the 106.8 TW h/y identified by CEPA, while the required balance (outsourced) of 20.6 TW h/y (19.3%) will come from hydropower. To the best of our research, there are no up-to-date and accurate data covering the entirety of crop production in Nigeria. This could be because there is no central body responsible for the segment.

Stratagem II: medium collection efficiency ($\beta = 40\%$; year 2025)

In carrying out CEPA for the year 2025, the target of electricity from carbon–neutral was determined as 207.5 TW h/y (see Fig. 4). Next, we will check if the potential amount of collected biomass is enough to meet the target. In this scenario, it is assumed that collection efficiency (β) is set

to 40%. The potential electricity for all selected biomass is shown in column 5 of Table 3. Note also that the average thermal energy of each biomass prototype has been maintained throughout for all stratagems. With the biomass collection efficiency set to 40%, the electricity from biomass is calculated as 172.6 TW h/y, using Eq. (1), which is insufficient to meet the target, i.e. 207.5 TW h/y. We must determine the outsourced electricity from other available carbon–neutral sources to match the deficit energy of about 34.9 TW h/y ($=207.5-172.6$). In stratagem I, hydropower generation was reported as 28 TW h/y, which is also insufficient for use. Hence, another source is needed to cover the insufficient amount of carbon–neutral energy, i.e. 6.9 TW h/y ($=34.9-28$ TW h/y).

To this effect, the study assumes as in the previous stratagems but this time due to the growing number of hydropower projects currently at the initiation stage (Monks 2017) that all of the 28 TW h of hydropower is utilised. Also, that 4% of the forecasted 181 TW h/y of solar thermal energy is utilised at this stage. Therefore, proceeded to obtain the optimal biomass supply chain network with the newly identified target based on CEPA. In this step, EPPD is reconstructed to depict the optimal generation mix network, as shown in Fig. 6.

Stratagem III: high collection efficiency ($\beta = 70\%$; year 2030)

This stratagem is set to analyse the situation where the biomass collection efficiency is set at 70%. The calculation of potential electricity for each of the selected biomass is like those in the strategems I and II. The specific information for the biomass under this stratagem is listed in Table 3 (column 6). The total potential electricity from all three biomass is determined as 302 TW h/y, while the renewable target identified by CEPA was 308.2 TW h/y. This implies a
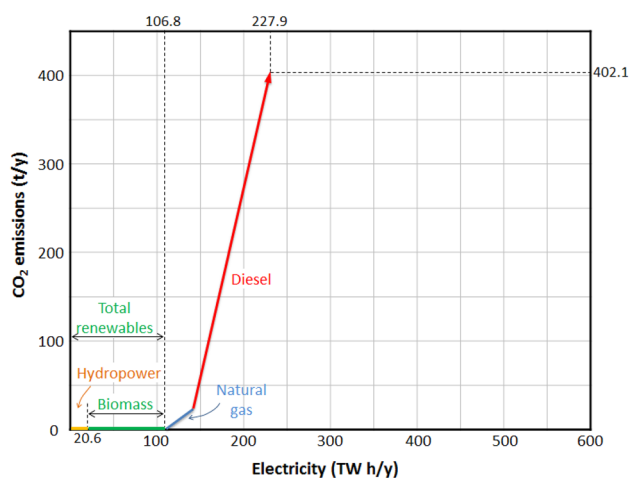
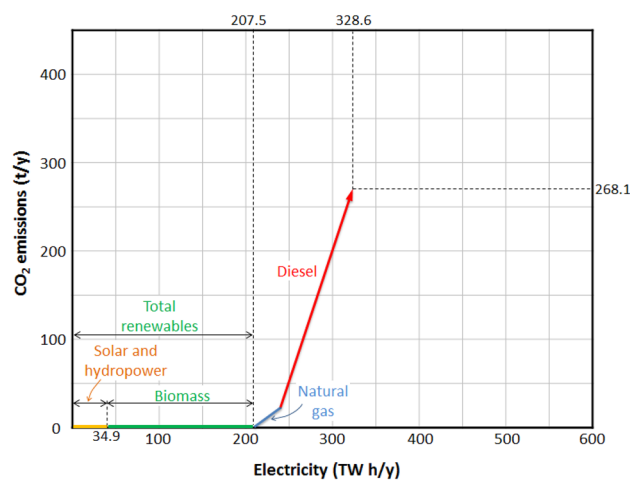

Fig. 5 EPPD for stratagem I (year 2020)

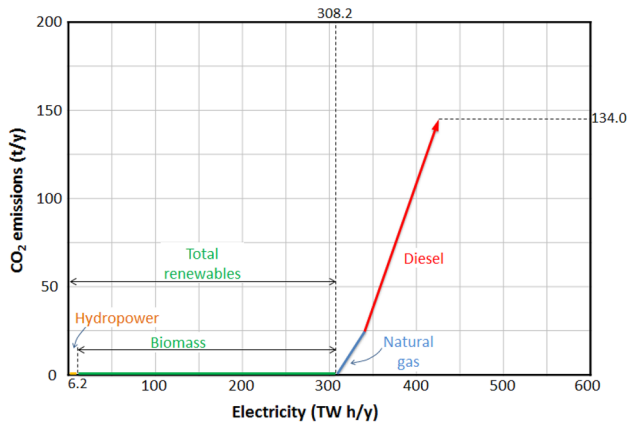**Fig. 6** EPPD for stratagem II (year 2025)

Fig. 7 EPPD for stratagem III (year 2030)

there is a deficit of 6.2 TW h/y to be outsourced from other carbon–neutral sources. Indistinguishable with stratagem II, hydropower generation can close the supply deficit of 6.2 TW h/y. Therefore, we can proceed to obtain the optimal biomass supply chain network with the newly identified target based on CEPA. In this step, EPPD is constructed to determine the optimal source target network, as shown in Fig. 7.
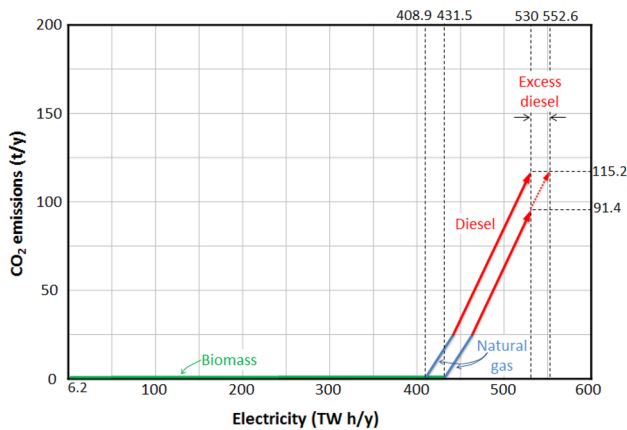

Fig. 8 EPPD for stratagem IV (year 2035)

Table 4 Targets for case scenarios

Scenario	CEPA identified target (TW h/y)	Biomass supply target (TW h/y)	Outsourced target (TW h/y)
I	106.8	86.2	20.6
II	207.5	172.6	37.0
III	308.2	302.0	6.2
IV	408.9	431.5	–

Stratagem IV: excellent collection efficiency ($\beta = 100\%$; year 2035)

In Stratagems 1, II and III, the total potential electricity from carbon–neutral biomass was insufficient to fulfil the target identified by CEPA. In this stratagem, presupposed that the biomass projects have reached maturity and productivity is significantly enhanced, the collection efficiency is set at 100%. Hence, the total potential electricity for each biomass is calculated by Eq. (1), summarised in the last column of Table 3. As shown in the table, the total potential electricity from all biomass residues is determined as 431.5 TW h/y, which satisfies the identified target of 408.9 TW h/y. Hence, generating power that matches the latter figure will fulfil the energy requirement for year 2035 (530.0 TW h/y), and yet reach the maximum CO_2 emission limit of 115.2 t/y (see Fig. 8). On the other hand, if one decides to send all biomass for power generation (i.e. generating 431.5 TW h/y power), the total CO_2 emission for the year 2035 is even lower than the targeted value (91.4 t/y). Note also that there will be 22.6 TW h/y ($= 552.6 - 530.0$ TW h/y) of excess power generated by diesel; which may be reduced from the power generation mix; this is also shown in Fig. 8. Table 4 shows the summary of all four stratagems.

Conclusion

The electricity sector in Nigeria has experienced consistently rapid growth in demand. However, a reverse growth of the central grid and lack of its accessibility has led to an exponential increase in net emissions. This study made use of CEPA for emissions planning and targeting for Nigeria. CEPA was used to identify the minimum quota of renewables to facilitate a diverse energy mix and mitigation of greenhouse gas (GHG) emissions. The aggregate renewable energy options suggest that renewable energy holds some potentials; thus, the study reinforces the idea that Nigeria has reliable energy sources that a 100% renewable energy target for electricity generation could be achieved. However, it is notable that energy databases in some circumstances are not up-to-date and incomplete. Future work will focus on the exploration of including municipal waste and industrial effluent that could facilitate the planning and management of the nation's total natural resources. Additionally, this methodology could also be extended to consider the targeting of segregated planning and energy techno-economic analysis.

Authors' contributions BS and SN conceived and planned the study. BS performed the analysis, data gathering and formatting of the article. BS

and DCYF wrote the main manuscript text. All authors reviewed the manuscript. DCYF and SN checked, edited and approved of the manuscript. All authors have read and collectively approved of the final manuscript.

Appendix

See Tables 5, 6, 7 and 8.

Table 5 Data for scenario 2035

Fuel source	Potential quantity of electricity (TW h)	Carbon emissions (t CO_2)
Hydropower	6.9	0.0
Natural gas	27.9	15.5
Diesel	495.2	521.0
Total	530.0	536.5

Table 6 Data for reduction strategies for years 2020, 2025, 2030 and 2035

Fuel source	Potential quantity of electricity (TW h)	Potential carbon emissions (t CO_2)
25% reduction in year 2020		
Zero-carbon	106.8	0.0
Natural gas	24.7	13.6
Diesel	96.4	388.5
50% reduction in year 2025		
Zero-carbon	207.5	0.0
Natural gas	24.7	13.6
Diesel	96.4	254.5
75% reduction in year 2030		
Zero-carbon	308.2	0.0
Natural gas	24.7	13.6
Diesel	96.4	120.4
100% reduction in year 2035		
Zero-carbon	408.9	0.0
Natural gas	24.7	13.6
Diesel	96.4	101.6

Table 7 Residues estimate from agricultural crops, 2010—Source (NESP 2015)

Crop	Component	Production area (000 hectares)	Production (000 tons)	Amount available (million tons)
Rice	Straw	4473.00	3368.24	7.86
	Husk			1.19
Maize	Stalk	7677.00	7676.85	10.75
	Cob			2.10
	Husk			0.92
Cassava	Stalk	42,533.00	42,533.17	17.01
	Peelings			76.56
Groundnut	Shells	3799.00	3799.25	1.81
	Straw			4.37
Soybean	Straw	356.00	365.06	0.91
	Pods			0.37
Sugarcane	Bagasse	481.00	481.51	0.11
	Tops/leaves			0.14
Cotton	Stalk	602.00	602.44	2.25
Millet	Straw	5171.00	5170.45	7.24
Sorghum	Straw	7141.00	7140.96	7.14
Cowpea	Shells	2860.00	3368.24	4.89
Total				145.60

Table 8 Other potential renewable energy sources in Nigeria

Resource	Potential	Current utilisation	Potential electricity (TW h/y)	Reference
Photovoltaic power source	$2.0\text{--}2.8 \times 10^{-9}$ TW h m^{-2} day^{-1}	28 TW h/y PV installed	181.0	Ogunmodimu and Okoroigwe (2018)
Hydro power	14.75×10^{-3} TW	1.96×10^{-3} TW	28.0	NESP (2015)
Wind	(2–4) ms^{-1} at 10 m height	–	25–90	Brimmo et al. (2017)
Nuclear	Unconfirmed	30 kW research reactor	–	Brimmo et al. (2017)
Municipal solid waste	0.53 kg/cap/day	–	26.7	Somorin et al. (2017)

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