Pathways to a fully sustainable electricity supply for Nigeria in the mid-term future

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DOI: 10.1016/j.enconman.2018.10.036

Energy Conversion and Management xxx (2018) xxx-xxx

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com

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ARTICLE INFO

Keywords:
Nigeria
Energy transition
Desalination
Photovoltaic
Energy system
Storage
Decarbonisation

ABSTRACT

Ambitious actions focused on rapid defossilisation of today's energy systems require greater urgency, in order to avert unmanageable impacts of climate change. Transitioning to a cost-effective and carbon-neutral energy system in Nigeria and across the globe by the second half of this century is vital. This study explores a paradigmatic pathway to a fully sustainable energy system for Nigeria, by 2050. The research approach is to simulate a cost-optimised transition pathway towards 100% renewable energy based power system for Nigeria, using a linear optimisation model. The model is based on hourly resolution for an entire year. The country researched is structured into 6 sub-regions. The optimisation for each of the 5-year time periods is carried out based on assumed costs and technological status until 2050 for all energy technologies involved. The levelised cost of electricity declines from 54 €/MWh in 2015 to 46 €/MWh in 2050 for the power sector in the Best Policy Scenario and further declines to 35 €/MWh with sector coupling. Whereas, the cost of electricity increased to 75 €/MWh in the Current Policy Scenario without greenhouse gas emission cost. The results clearly reveal that integrating a renewable energy technology mix with a wide variety of storage technologies is the most competitive and least cost electricity option for Nigeria in the mid-term future, as indicated by the Best Policy Scenario. In particular, the compatibility and predominant role of solar photovoltaics and batteries is paramount towards a rapid transition of Nigeria's power sector, due to highly favourable economics. This study concludes with the implications of a stable and supportive policy environment, transitioning to a defossiliated energy system in Nigeria could be achieved in the mid-term future. This study is the first of its kind in full hourly resolution for Nigeria, and demonstrates the need for carrying out detailed analyses in examining gaps in energy transition understanding based on various policy constraints for developing countries in comparable climates.

Nomenclature

A-CAES	adiabatic compressed air storage
BPS	best policy scenario
CAPEX	capital expenditure
CCGT	combined cycle gas turbine
CHP	combined heat and power
CPS	current policy scenario
CSP	concentrating solar thermal power
DISCOs	Electricity Distribution Companies in Nigeria
ECN	Electricity Corporation of Nigeria
ESPR	electric power sector reform
FMWR	Federal Ministry of Water Resources
GENCOs	power generation companies in Nigeria
GT	gas turbine
HVDC	high voltage direct current
LCOC	levelised cost of curtailment
LCOE	levelised cost of electricity
LCOS	levelised cost of storage
LCOT	levelised cost of transmission
NDA	Niger Dams Authority
NEEAP	National Energy Efficiency Action Plan
NEPA	National Electric Power Authority
NESI	Nigerian Electricity Supply Industry
NREEP	National Renewable Energy and Efficiency Policy
OCGT	open cycle gas turbine
OPEX	operational expenditure
PHCN	Power Holding Company of Nigeria
PHS	pumped hydro storage
PV	photovoltaic
RE	renewable energy
RoR	run-of-river
SHS	solar home system
SNG	synthetic natural gas
SSA	Sub-Saharan Africa

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https://doi.org/10.1016/j.enconman.2018.10.036
Received 10 August 2018; Received in revised form 11 October 2018; Accepted 13 October 2018
Available online xxx
0196-8904/

ST	steam turbine
SWA	State Water Agency
TRANSCO	Transmission Company of Nigeria
TES	thermal energy storage
UN	United Nations
VRE	variable renewable energy
WACC	weighted average cost of capital

1. Introduction

Transitioning away from the contemporary to a net zero emission energy system around the middle of the 21st century is of paramount importance [1], in order to keep global temperature rise well below 2 °C above pre-industrial levels and pursuing efforts to limit this to 1.5 °C [2]. Staying under 2 °C requires an urgent shift towards defossiliated energy systems [3]. Renewable energy (RE) sources are vital to avoid the unmanageable impacts of climate change [4]. In addition, RE sources could address the current electricity supply gaps and future demands in many countries in Sub-Saharan Africa (SSA), as well as in Nigeria [5]. Electricity demand in West Africa grew from 29 TWh in 2000 to 61 TWh in 2012; the highest demand in the region is in Nigeria, which accounts for about 50% of the total demand [6]. By 2040, total electricity demand in Nigeria is expected to reach 291 TWh according to the International Energy Agency (IEA) [6].

Nigeria faces an enormous challenge with access to electricity [7]. In spite of the country's abundant oil and gas resources, it still suffers from huge under-capacity in electricity generation, with frequent power outages driving consumers towards wide-spread use of costly backup generators [6]. The Nigerian power sector is not yet able to meet the entire power needs of the country [8]. As Akuru et al. [7] question, whether there could ever be stable and cost-effective electricity in Nigeria. Nigeria's on-grid electricity consumption is low, at 126 kWh per capita compared to other developing countries [9]. The per capita electricity consumption of Ghana and South Africa are 2.9 times (361 kWh) and 31 times (3926 kWh) higher than that of Nigeria, respectively [9]. More than 90 million people in Nigeria still lack access to grid electricity, which represents 55% of the country's population [6]. Unmet power demand results in load shedding, blackouts, and reliance on expensive diesel backup generators [10]. In 2012, an estimated amount of 16 TWh electricity demand was served by backup generators in SSA, and Nigeria accounts for about three-quarters of the electricity supplied by backup generators in the region [11]. The cost of electricity from generators (0.14–0.22 €/kWh) are more than twice as expensive as grid-based power (0.06–0.09 €/kWh) in Nigeria [9].

Furthermore, the country's economic growth is hampered by the prevalent energy crisis [11]. The Nigerian government aims at a holistic economy transformation and have identified various barriers to the country's economic development, which includes the erratic power supply, poor and crumbling infrastructure and over-reliance on the oil sector [11]. To address the erratic power supply, the Nigerian electricity vision 30:30:30 recognises the significance of RE sources to complement the current fossil fuel consumption and guarantee energy security. By 2030, on-grid capacity is expected to reach 30 GW, of which RE will contribute a 30% share of the total electricity mix [12]. There are plans underway to build nuclear and coal power plants in Nigeria [12]. Beyond environmental and public health risk of building fossil-fuelled power plants [13], most nuclear power plants incurred construction period overruns [14] and substantial cost escalation [15]. According to [16], 180 nuclear reactors representing 178 GW and 459 bUSD worth of investment, incurred almost 231 bUSD in cost overruns. In addition, the cost of providing electricity from RE technologies in particular solar photovoltaic (PV) and wind are increasingly competitive with fossil-based power plants. The global weighted average levelised cost of electricity (LCOE) of utility-scale solar PV fell by 68% between 2010 and 2017 [17]. For instance, the current tariffs for new solar PV and wind (0.041 €/kWh) are now 40% cheaper than new baseload coal (0.069 €/kWh) in South Africa [18]. A recent study on cost comparison of various power technologies for Nigeria reveals that RE technologies are one of the strongest options to meet the power need of Nigeria in the most cost competitive way [19].

Recent studies have demonstrated the possibility of achieving a 100% renewables based power systems for cases such as Nigeria [5], SSA [10], Northeast Asia [20], Europe [21] and global [22]. These studies have shown that deep decarbonisation of the future power system is possible taking into account technical, economic and societal constraints, but it is also the least cost electricity option with utmost societal welfare. In addition, the Paris Agreement and the Sustainable Development Goal 7 (SDG 7) can be well supported by the deployment of small and large scale RE technologies, in view of tackling the two main challenges faced globally; climate change and widespread energy poverty [3]. The current electricity deficit and rising demand in Nigeria necessitates rapid response in bridging the gap between demand and supply [12], due to its growing population and unprecedented economic progress [10]. Therefore, tackling the plague of recurrent power outages and rising electricity demand in a way that is economically sustainable and safeguards livelihoods in Nigeria [7], which requires the deployment of RE infrastructure as a key solution with benefits that are multifaceted [10]. Nigeria has vast untapped RE resources [8], integrating RE technology mix with a wide variety of storage technologies could be competitive and the least cost electricity option for Nigeria [19].

This research presents the importance of carrying out an analytical and comprehensive investigation, when assessing least cost electrification options and transition pathways for developing countries, like Nigeria, under various policy constraints. The analysis for Nigeria is exemplary for developing countries of comparable climates. To better understand the transition pathways, eight scenarios have been defined based on governmental intended transition plans (Current Policy Scenarios) and zero emission scenarios (Best Policy Scenarios), which full match the targets of the Paris Agreement. Further, the impact of various factors such as greenhouse gas (GHG) emissions cost and sector coupling are assessed as well. The chosen optimisation modelling approach synthesises and reflects in-depth insights on how demand of different energy sectors such as power, non-energetic industrial gas and desalination can be met. The optimisation for each period, modelled in 5-year intervals, is carried out based on assumed costs and technological status until 2050. The paper is structured as follows: Section 2 presents an overview of the Nigerian power sector. The research methodology is described in Section 3. Results are presented and analysed in Section 4. In Section 5, the results are discussed and compared with related studies. Conclusion and policy implications are presented in Section 6.

2. The Nigerian power sector

The history of electricity generation in Nigeria dates back to 1886, when two generating plants were installed to serve the Lagos Colony. In 1929, Nigeria's first utility company, the Nigerian Electricity Supply Company was established [23]. Further development in the sector, led to the establishment of the Electricity Corporation of Nigeria (ECN) in 1951 to oversee electricity distribution in the country [23]. In 1962, the Niger Dams Authority (NDA) was established to oversee hydropower development [24]. The NDA oversaw power generation, while distribution and sales were undertaken by ECN. However, the ECN and NDA were merged in 1972 and resulted in the formation of the National Electric Power Authority (NEPA), which was responsible for generation, transmission, and distribution of electricity for the entire country. Reforms in the power sector in 2005 resulted in unbundling of the NEPA and a renaming to Power Holding Company of Nigeria (PHCN) [25].

In spite of the long existence of electricity in the country and reforms, the power sector development has been at a slow rate. Today, gas and hydropower plants dominate the on-grid power generation capacity in Nigeria, which represent 86% and 14% of the total installed capacity, respectively [19]. The country's power sector consists of three main sub-sectors [8], namely; generation companies (GENCOs), transmission company (TRANSCO) and distribution companies (DISCOs) as shown in Fig. 1 [26]. Currently, there are 22 gas and 3 hydro on-grid generating plants operating in the Nigerian electricity supply industry (NESI) as shown in Fig. 2, concentrated in Southern Nigeria, with a total installed capacity of 12,522 MW, and available capacity of 7141 MW [9]. The management of Transmission Company of Nigeria is contracted to Manitoba Hydro International (Canada). The national grid consists of about 5524 km of 330 kV and 6802 km of 132 kV transmission lines [12]. The electricity distribution company of Nigeria consists of 11 companies across the country, as shown in Fig. 1 [8]. The distribution grid is operated mainly on 33 kV (medium voltage) and 11 kV (low voltage), comprising a network of over 24,000 km [23].

The available capacity could be used for electricity generation, but is constrained by internal plant issues, majorly maintenance and repair issues. In addition, Nigeria's power grid faces daily challenges [27], due to water shortage, high frequency due to demand imbalances, in-

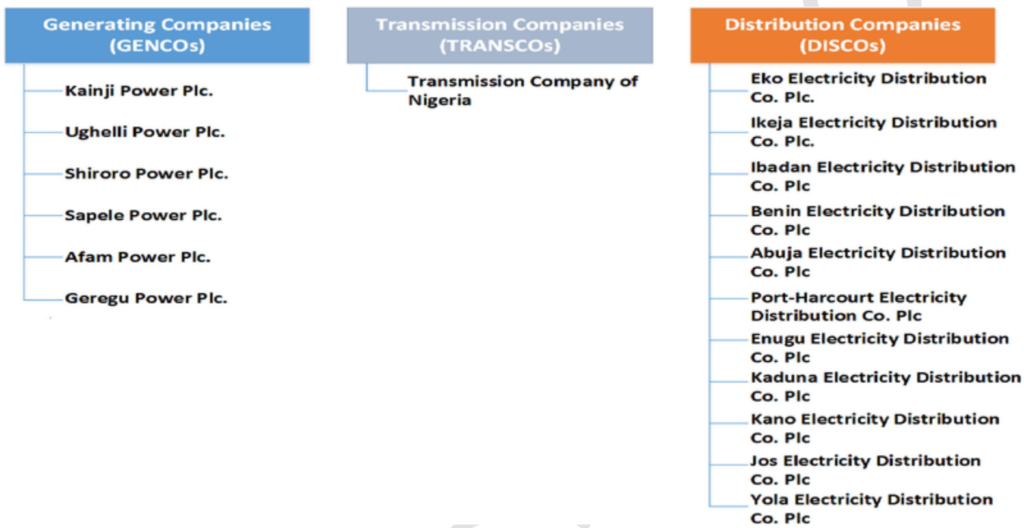

Fig. 1. Overview of Nigeria's generation, transmission and distribution sector [26].

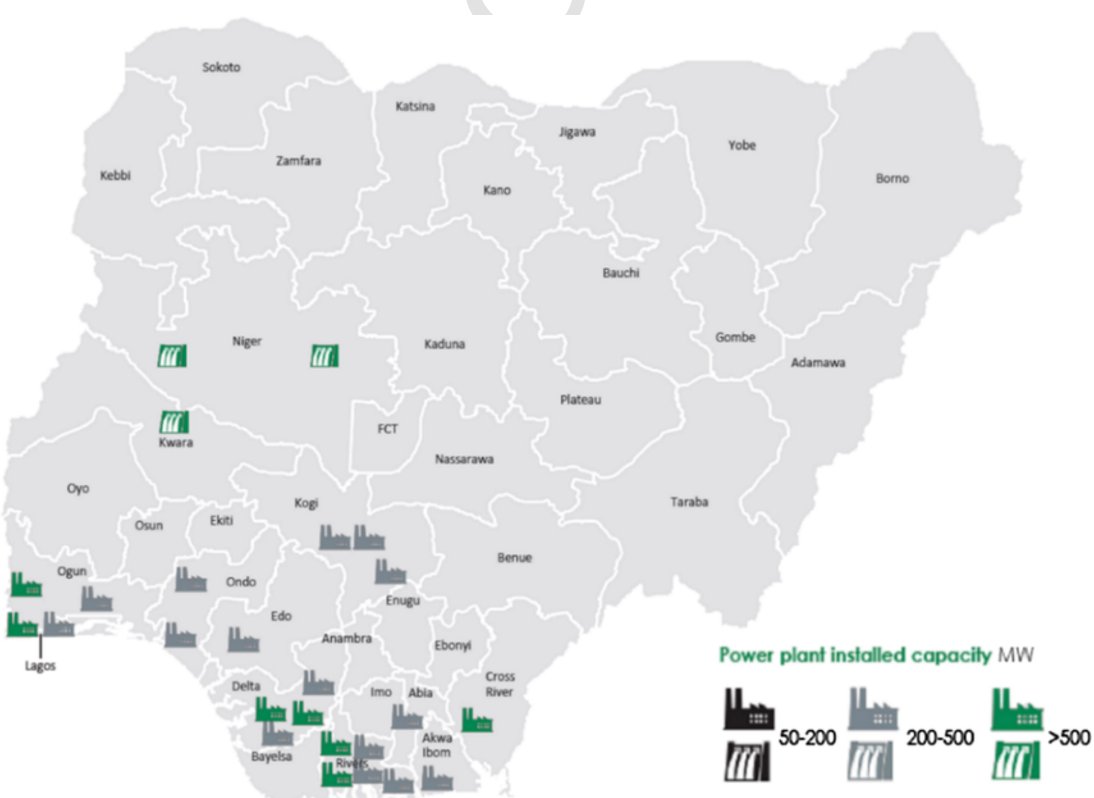

Fig. 2. Nigeria's 25 on-grid power plants locations [9].

sufficient gas supply, and line constraints due to inadequate grid infrastructure as shown in Fig. 3 [9]. These constraints have led to a mismatch in demand and supply, and over-reliance on backup generators, among other issues. In addition, the power industry loses an average of 6 m€ (1.4 billion Naira) in revenue daily, due to these constraints. Fig. 4 shows the revenue lost to various constraints in the Nigerian power industry.

For many years, the power sector was owned, managed and controlled by the government. The state-owned monopoly utility NEPA, throughout its existence, failed to meet the country's electricity need [25]. Upon the advent of the democratic government in 1999, the Federal Government of Nigeria has committed huge financial investments of about 14 b€ to refurbish the power sector, but without proportionate outcomes [25]. One of the key measures taken by the government to revamp the power sector was privatisation of power assets [8]. To this end, various policy measures were established in view of the privatisation [23]. In 2005, the Electric Power Sector Reform (ESPR) Act was enacted to allow private investors involvement in the previous governments' monopolised sector. Fig. 5 shows the structure of the post-reform power sector [29]. Besides hydropower, Nigeria does not yet have any large RE-based generating plants, contributing to its on-grid electricity, in spite of the country having huge RE potential and energy market prospects.

Fig. 6 shows the solar and wind resources maps for Nigeria. The data are provided by NASA [30,31], reprocessed by the German Aerospace Center [32] and converted to full load hours according to Bogdanov and Breyer [20] and Afanasyeva et al. [33]. However, a fundamental action towards RE development in Nigeria lies in a strategic and supportive policy direction by the Nigerian government towards a progressive RE master plan [7]. Such policy, legal and institutional framework are at their nascent stage in Nigeria [8] and are foreseen to foster RE development [12]. In 2015, the Federal Government of Nigeria approved the National Renewable Energy and Efficiency Policy (NREEEP), which is the country's first ever RE-specific policy, which provides the descriptive framework for energy efficiency and RE development in Nigeria. The country targets to increase its total on-grid capacity from 4 GW in 2015 to 30 GW by 2030 [12]. This target was determined through the process of developing the National Renewable Energy Action Plan (NREAP) and National Energy Efficiency Action Plan (NEEAP), as stated in the NREEEP 2015. The share of on-grid RE

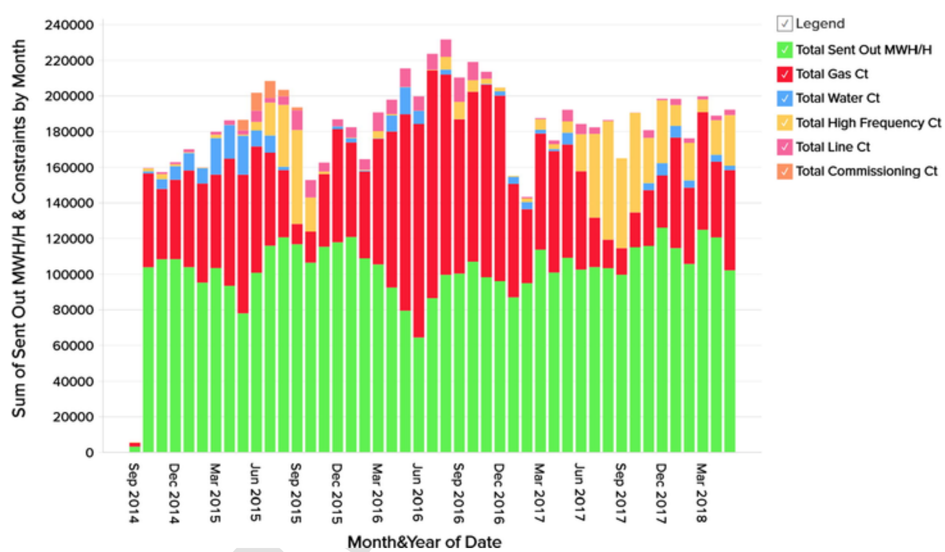

Fig. 3. Electricity generation and constraints (Ct) in Nigeria [28].

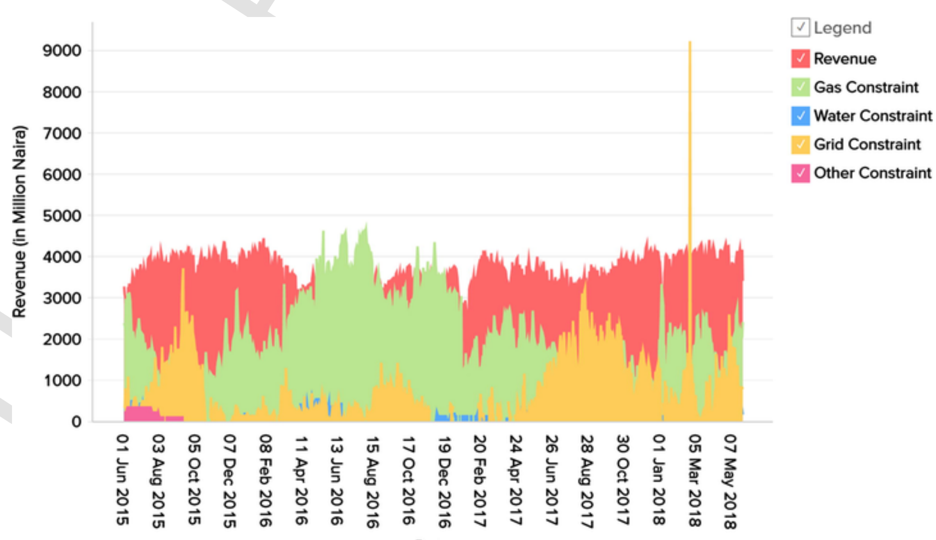

Fig. 4. Revenue lost to constraints in the Nigeria power sector [28] (1 billion Naira is equivalent to 2 m€).

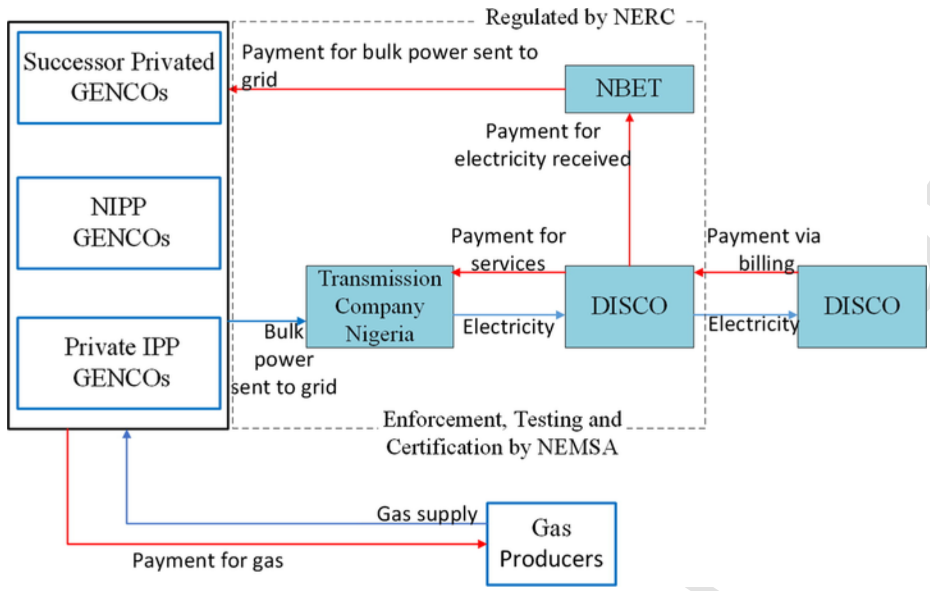

Fig. 5. Post-reform power sector structure [29].

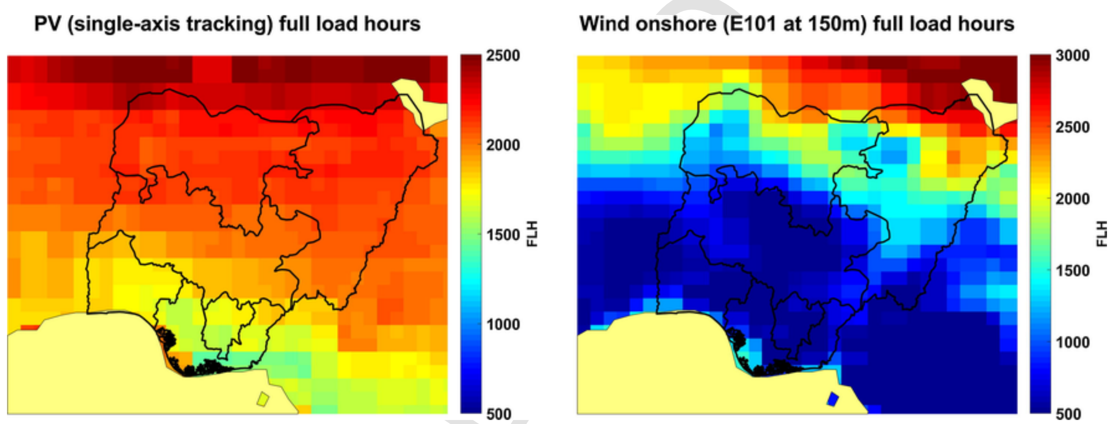

Fig. 6. Maps of Nigeria showing annual full load hours for solar PV single–axis tracking (left) and onshore wind (right) for the year 2005.

supply is expected to increase from its present 1.3% in 2015 to 16% by 2030 in the NREEEP 2015. However, upon the completion and endorsement of NREAP 2016, the target was revised to a 30% share of RE supply by 2030.

3. Research methods

The research approach applies linear optimisation modelling in determining the optimal investment and electricity generation technology mix, needed to satisfy electricity demand in Nigeria by 2050 [22]. A linear optimisation energy system tool, the LUT Energy System Transition model [20], is used to simulate the Nigerian power system. The model was designed and developed to analyse an energy transition from the current (as of the beginning of 2015) fossil based-system to a 100% RE-based power system by 2050, covering the demand of power, non-energetic industrial gas and desalination sectors. The transition is modelled in 5-year steps from 2015 to 2050, and is carried out based on assumed costs and technological status for all energy technologies involved. The electricity generating plants required for the energy transition from 2015 to 2050 is considered according to Caldera et al. [34] and based on Farfan and Breyer [35]. Two essential constraints are taken into consideration as the basis for the energy system transition modelling. Firstly, after 2015, no new fossil-based power plants are installed. The existing fossil-based power plants are gradually phased out based on their technical lifetimes. However, the installation of gas turbines is permitted after 2015 due to lower carbon emission, high efficiency of the technology, and in particularly due to the possibility to accommodate bio-methane and synthetic natural gas in the system, so that a fuel shift towards sustainable fuels can be realised. Secondly, RE capacity growth cannot exceed 4% per year, in order to prevent system disruptions.

3.1. Model structure

The LUT Energy System Transition model is developed for comprehensive analyses of energy transition from current energy systems to 100% RE-based systems. The model is based on linear optimisation with an hourly resolution of the energy system parameters for an entire year, under a set of applied constraints, assumptions for the future RE powered system and demand. Detailed model description, equations and applied constraints can be found in [20]. The model is compiled using MATLAB [36], while the optimisation is carried out in MOSEK [37]. Fig. 7 shows the flow diagram of the main input parameters and outputs of the model. A full set of technical and financial assumptions used in this study are presented in the Supplementary Material (Table S1). The target function of the model optimisation is to minimise the total annual energy system cost, which is calculated as the sum of annual costs of the installed capacities of each technology, costs of energy

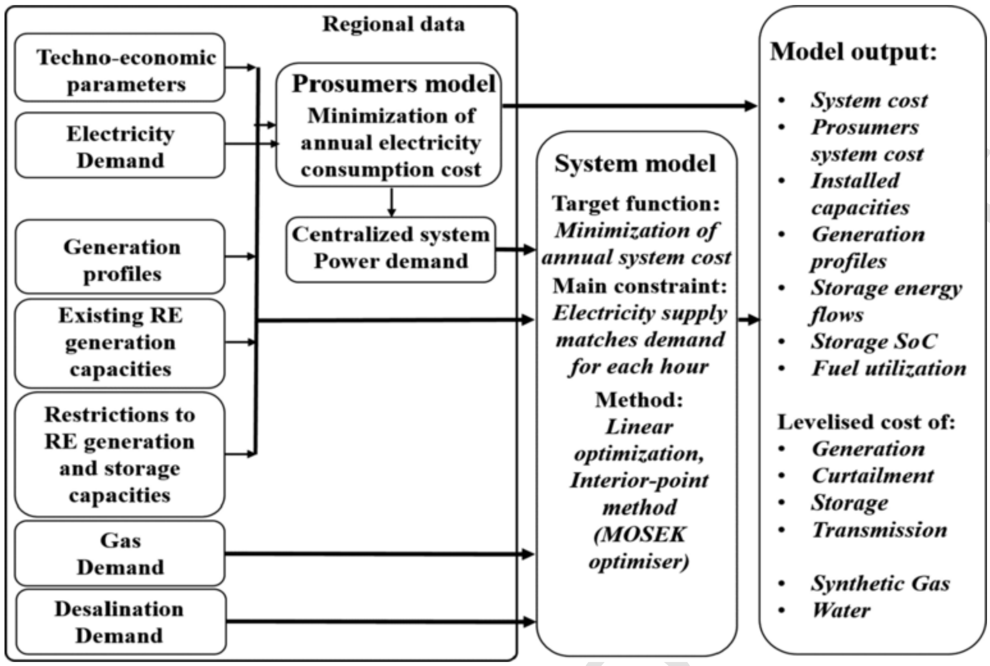

Fig. 7. Main inputs and outputs of the LUT Energy System Transition model [22].

generation, and costs of generation ramping. In addition, the energy system consists of distributed generation and self-consumption of residential, commercial and industrial consumers. The transition analysis considers the potential of the prosumer market segment as an essential aspect of system planning. Thus, another mini-transition hourly model describes the prosumers PV systems and battery development capacity. Prosumers can install rooftop PV and lithium-ion batteries, depending on the cost, or buy electricity from the grid. The target function of the prosumers is the minimisation of cost of electricity consumed. This cost is calculated as the sum of self-generation cost, annual cost, and cost of electricity consumed from the grid. Excess electricity generated by prosumers can be sold to the overall energy system for 0.02 €/kWh.

3.2. Applied technologies

The main technologies applied for the Nigerian energy system modelling can be divided into four main categories:

- Electricity generation technologies
- Electrical energy storage technologies
- Electricity transmission technologies
- Energy sector bridging technologies to provide more flexibility to the energy system

Fig. 8 shows the block diagram of the energy model and all applied technologies for the transition. The RE generation technologies intro-

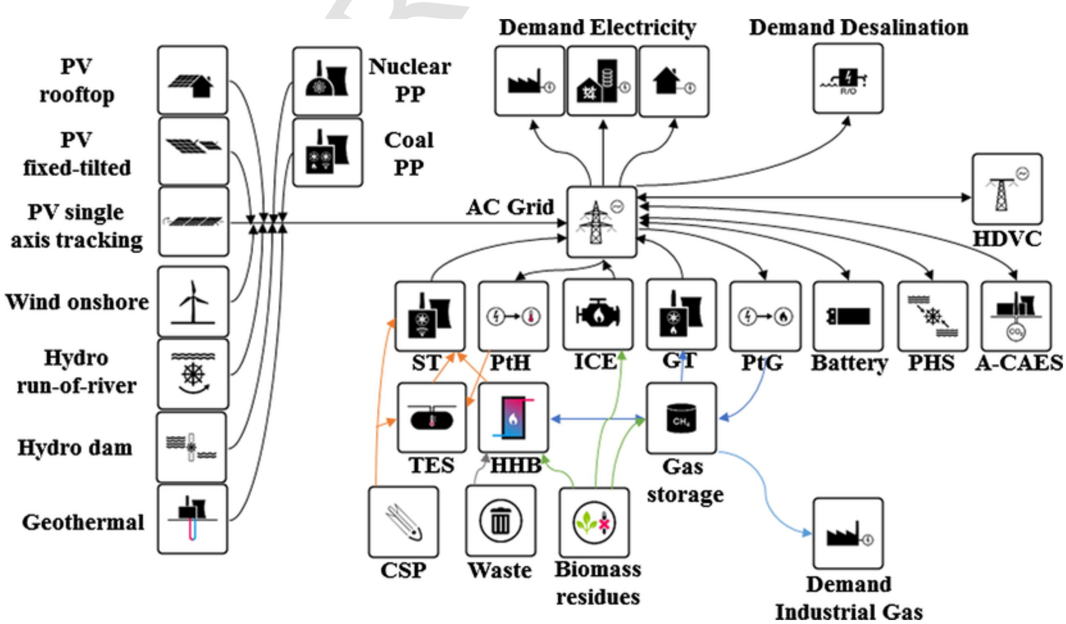

Fig. 8. Block diagram of the LUT Energy System Transition model used for Nigeria [22].

duced in the model include various PV technologies (ground-mounted and rooftop solar PV systems), hydropower (run-of-river and reservoir based), biomass plants (solid biomass and biogas), wind onshore turbines, geothermal power plants, concentrating solar thermal power (CSP) and waste-to-energy power plants. While the fossil generation technologies are coal, oil, open cycle gas turbines (OCGT) and combined cycle gas turbines (CCGT), as well as nuclear power. Due to the variability of RE and to ensure a steady supply of electricity, the RE technologies are complemented by various storage technologies. These technologies include pumped hydro storage (PHS), Li-ion batteries assumed to serve residential and system storage, thermal energy storage (TES), adiabatic compressed air energy storage (A-CAES) [38] and power-to-gas (PtG) [39]. Energy sector bridging technologies such as gas from PtG process and seawater reverse osmosis (SWRO) desalination [34] provide more flexibility to the energy system. PtG includes synthetic natural gas (SNG): methanation, water electrolysis, gas storage, carbon dioxide (CO_2) direct air capture, and gas turbines (OCGT and CCGT). Due to the absence of hydrogen and CO_2 storage, PtG technologies operate in synchronisation. In addition, the model uses a 48-hour biogas buffer storage, and part of the biogas can be upgraded to biomethane and is introduced into the gas storage.

3.3. Country division

The multi-node approach used in the model enables description of any desired configuration. Based on this approach, Nigeria is divided into six sub-regions, according to political zoning of the country, namely, North-East (NIG-NE), North-West (NIG-NW), North-Central (NIG-NC), South-East (NIG-SE), South-South (NIG-SS) and South-West (NIG-SW). Each of the sub-regions represents a node. The nodes are interconnected via transmission lines, within the country borders, as shown in Fig. 9.

3.4. Financial and technical assumptions

The financial and technical assumptions for all the energy system components are made in 5-year time steps, which include capital expenditures (CAPEX), operational expenditures (OPEX) and lifetimes, from 2015 to 2050, and are provided in the Supplementary Material (Table S1). Weighted average cost of capital (WACC) is set to 7% in this study, but for residential PV prosumers, WACC is set at 4% due to lower financial return requirements. The technical assumptions concerning storage technologies, efficiency numbers for generation, and power losses in HDVC power lines and converters, can be found in the Supplementary Material (Tables S2–S4). The electricity prices for residential, commercial and industrial consumers for the year 2015 were retrieved from electricity DISCOs tariff document available online at the Nigerian Electricity Regulatory Commission (NERC) website [40]. The electricity price was calculated until 2050 according to Gerlach et al. [41] and Breyer and Gerlach [42]. The electricity price for all sub-regions are available in the Supplementary Material (Table S5).

The upper limits for all RE technologies were estimated according to Bogdanov and Breyer [20] and lower limits are obtained from Farfan and Breyer [35]. Upper and lower limits of RE and fossil fuels are provided in the Supplementary Material (Tables S6 and S7). For all other technologies, upper limits are not specified. However, for solid biomass residues, biogas and waste-to-energy plants it is assumed, due to energy efficiency reasons, that the available and specified amount of fuel is used during the year. Key power capacities required for the energy transition for Nigeria are provided in the Supplementary Material (Tables S8–S13). The current transmission line capacities connecting the sub-regions within the country were taken from [43]. The existing power grid, its development, and overall impact on electricity transmission and distribution losses were taken into account in the study.

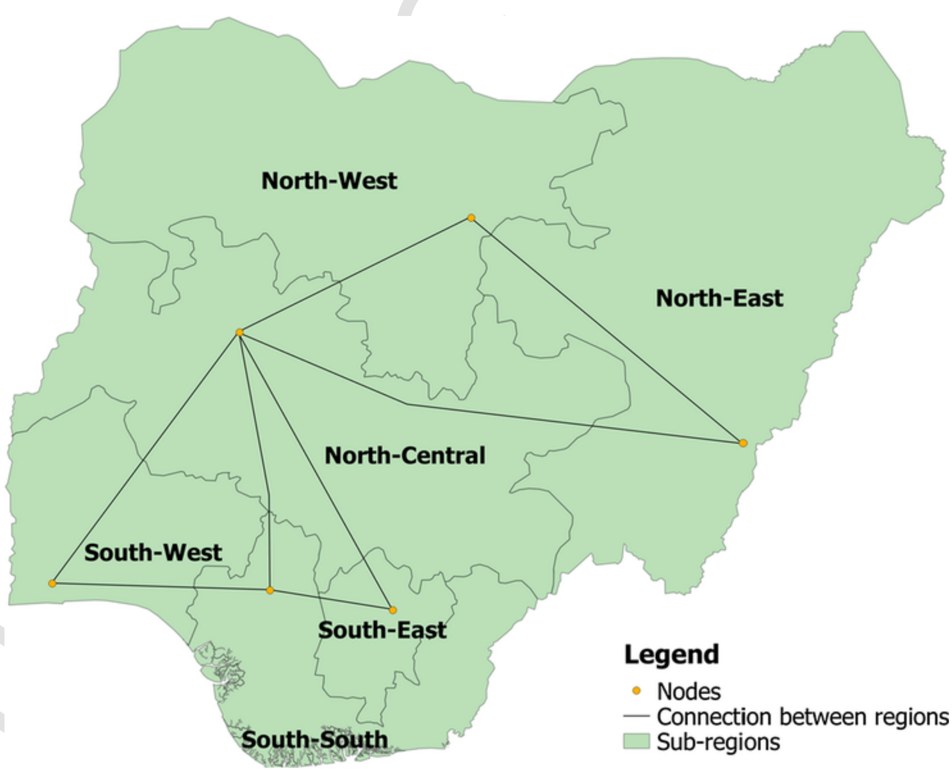

Fig. 9. Nigeria sub-regions and transmission lines configuration.

3.5. Renewable resource potential

The feed-in profiles for PV optimally tilted, PV single-axis tracking, wind energy and CSP are calculated according to Bogdanov and Breyer [20] and Afanasyeva et al. [33], based on resource data provided by NASA [30,31], reprocessed by the German Aerospace Center [32]. The feed-in values for hydropower are computed based on monthly resolved precipitation data for the year 2005 as a normalized sum of precipitation in the sub-regions. Such an estimate leads to a good approximation for the annual generation of hydro power plants [44]. Full load hourly data of various resources are presented in the Supplementary Material (Tables S14–S19). The resource profiles visualised in an hourly resolution can be found in the Supplementary Material (Figs. S1 and S2). In addition, the storage throughput is available in the Supplementary Material (Tables S20–S25).

The potentials for waste and biomass resources for Nigeria are taken from German Biomass Research Centre [45] and classified according to Bogdanov and Breyer [20]. The costs for biomass are calculated using data from the IEA [46] and Intergovernmental Panel on Climate Change (IPCC) [47]. For solid waste, a 50 €/ton gate fee was assumed for 2015, which increased up to 100 €/ton in 2050.

The geothermal potentials are calculated for the sub-regions based on the available information related to heat flow rate [48] and ambient temperature of the surface for the year 2005 [49]. For the sub-regions where the heat flow data were not available, extrapolation was performed to get the required data. The potential is estimated based on the available data [50], different temperature levels [51] and available heat at the mid-point of a 1 km thick deep layer and between the depths of 1–10 km globally with 0.45° × 0.45° spatial resolution [52].

3.6. Demand

Electricity demand data are taken from [11], and are verified with data provided in [12]. The electricity demand until 2050 is provided in the Supplementary Material (Table S5). The hourly load profiles for electricity are calculated as a fraction of the total demand in each sub-region based on synthetic load data weighted by the sub-regions population [53]. For seawater desalination, SWRO is mainly used in this study due to its low-cost and energy efficiency advantages from 2020 onwards [54]. Nonetheless, multiple effect distillation (MED) dominates in the start of the transition and complements from 2020 onwards. The required desalination capacity, technical constraints and financial assumptions from 2015 to 2050 are calculated by using the methodology described in [54]. The non-energetic industrial gas demand data are taken from IEA statistics website [55] and extrapolated until the year 2050 based on IEA's assumption for non-energy gas demand growth rate for Nigeria [6].

3.7. Scenarios

In this study six scenarios have been developed, which are briefly described in Table 1. The scenarios explore pathways to a 100% RE system in the mid-term future, covering the demands of the power, non-energetic industrial gas and desalination sectors.

4. Results

This section presents the findings of the modelling outcomes for the Nigerian energy transition pathways in the mid-term future. Financial implication of the energy transition, installed capacities, electricity generation mix, transmission and storage are analysed in this section. Order of the figures in the entire paper are as follows: Figure (a) is assigned to BPS-1, Figure (b) to BPS-2, Figure (c) to BPS-3, Figure (d) to CPS-1, Figure (e) to CPS-2, and Figure (f) to CPS-3.

Table 1
Overview of the studied scenarios.

Scenario name	Description
Best Policy Scenario (BPS-1) – Power only scenario	The target of the LUT model is to reach 100% RE by 2050. In addition, GHG emission cost is applied in the model to restrict fossil power plants. In this scenario, only electricity demand is covered
Best Policy Scenario (BPS-2) – Power only scenario (planned hydropower capacity considered)	This scenario is the same as the above scenario. In addition, the planned hydropower capacity is also considered. For instance, Zungeru hydropower project of 0.7 GW and Mambilla project of 3.0 GW are to be installed in 2020 and 2025 [56], respectively, during the transition and according to the respective planning [12]
Best Policy Scenario (BPS-3) – Integrated scenario	In this scenario, power, SWRO desalination and non-energetic industrial gas sectors demand is covered
Best Policy scenarios without GHG emission cost (BPSnoCC)	In these scenarios, GHG emission cost is not considered for the Best Policy Scenario 1 and 2. The financial implication, installed capacities and generation for Best Policy Scenario 1 no GHG emission cost (BPS-1noCC) and Best Policy Scenario 2 no GHG emission cost (BPS-2noCC) are only discussed in Section 4.9
Current Policy Scenario (CPS-1)	In this scenario, the country's target relating to electricity capacity mix up to 2030 is considered according to [12]. However, the post-2030 capacity mix is extrapolated up to 2050.
Current Policy Scenario (CPS-2) – no GHG emission cost	This scenario is the same as the previous described scenario, except that in this scenario GHG emission cost is not considered in the modelling
Current Policy Scenario (CPS-3)	After 2030, no new fossil power plants are allowed except nuclear power plants, because the country aims at reaching 4.8 GW installed capacity of nuclear by 2035

4.1. Levelised cost of electricity

The LCOE obtained for all the scenarios are shown in Fig. 10. The average financial results for the scenarios are expressed as LCOE, which includes all generation, storage, curtailment, transmission, fuel and GHG emission costs. The LCOE trend from now until 2050 varies for the different scenarios. Firstly, the system LCOE trend during the transition for the Best Policy Scenarios is observed as shown in Fig. 10(a)–(c). In the BPS-1 and BPS-2, the LCOE increased slightly around 2025, beyond 2025 the system LCOE further declines to 48 €/MWh and 46 €/MWh by 2050, respectively. However, the LCOE remains stable until 2030 and further declines to 34 €/MWh by 2050 in the BPS-3. The increase observed in the LCOE trend in the Best Policy Scenarios, particularly in BPS-1 and BPS-2, around 2025 are due to investment requirements. From 2030 onwards, the system LCOE steadily declines, signifying the impact of low-cost RE technologies, in particular solar PV and battery technologies in the Best Policy Scenarios. By 2050, the system LCOE is mainly dominated by cost of generation and storage, as solar PV contributes to the largest share of electricity generation and its complementarity by battery storage. Fig. 10(d)–(f) presents the corresponding LCOE for the Current Policy Scenarios. Fuel and GHG emission costs contribute to more than half of the total LCOE by 2050 in the Current Policy Scenarios, except in CPS-2 because GHG emission cost was not taken into account. This also led to LCOE deviation in 2015 for the CPS-2 in comparison to other scenarios. By 2050, the LCOE is 120 €/MWh, 75 €/MWh and 100 €/MWh in CPS-1, CPS-2 and CPS-3, respectively, as shown in Fig. 10(d)–(f). Additional financial results for all the scenarios are available in the Supplementary Material (Figs. S3–S5).

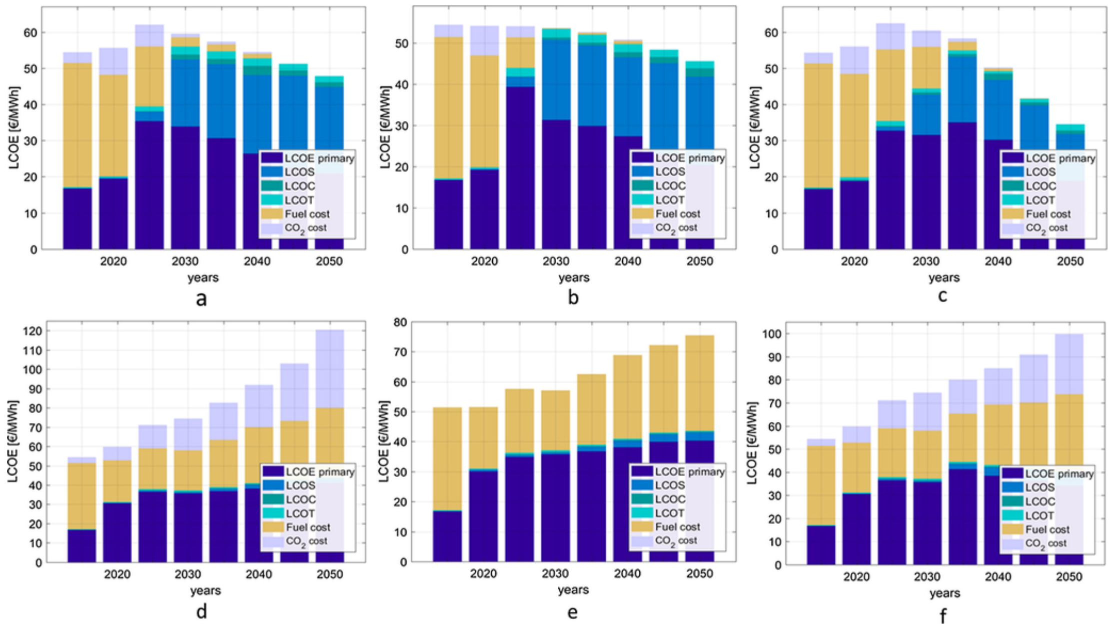

Fig. 10. Contribution of levelised cost of primary generation (LCOE primary), storage (LCOS), curtailment (LCOC), transmission (LCOT), fuel cost and GHG emission cost for BPS-1 (a), BPS-2 (b), BPS-3 (c), CPS-1 (d), CPS-2 (e), and CPS-3 (f).

4.2. Installed capacity and electricity generation mix

As a result of under-capacity and increasing electricity demand in Nigeria, investments in electricity generation capacity are needed. The total installed capacities for all technologies and the respective electricity generation mix are shown in Figs. 11 and 12, respectively. The installed capacities in the Best Policy Scenarios are visualised first as shown in Fig. 11(a)–(c). Fig. 11(a)–(c) shows how the fossil gas and hydropower dominated power system in 2015 gradually becomes less attractive. Solar PV contributes significantly to the power system from 2025 onwards in all the Best Policy Scenarios, in particular single-axis tracking PV. By 2050, the total solar PV capacity is 181 GW of which single-axis tracking PV contributes 125 GW in BPS-1. Whereas in BPS-2 and BPS-3, single-axis PV contributes 118 GW of 174 GW of total PV capacity and 272 GW of 328 GW of total PV capacity, respectively. PV prosumers account for the remaining share of the total PV installed capacities in each of the scenarios. Asides solar PV, a variety of technologies in the mix can be seen in Fig. 11(a)–(c), as investments occur in various technologies in all the Best Policy Scenarios, which includes biomass, geothermal, wind and gas turbine (OCGT and CCGT). Whereas, CSP does not feature in the energy mix, as it is less competitive in comparison to solar PV and battery energy storage. Regarding electricity generation in the Best Policy Scenarios, solar PV increasingly covers most of the power system demand as shown in Fig. 12(a)–(c), while wind, hydropower, geothermal and bioenergy complement it. The graphical results for the primary electricity generation in all scenarios can be found in the Supplementary Material (Fig. S6).

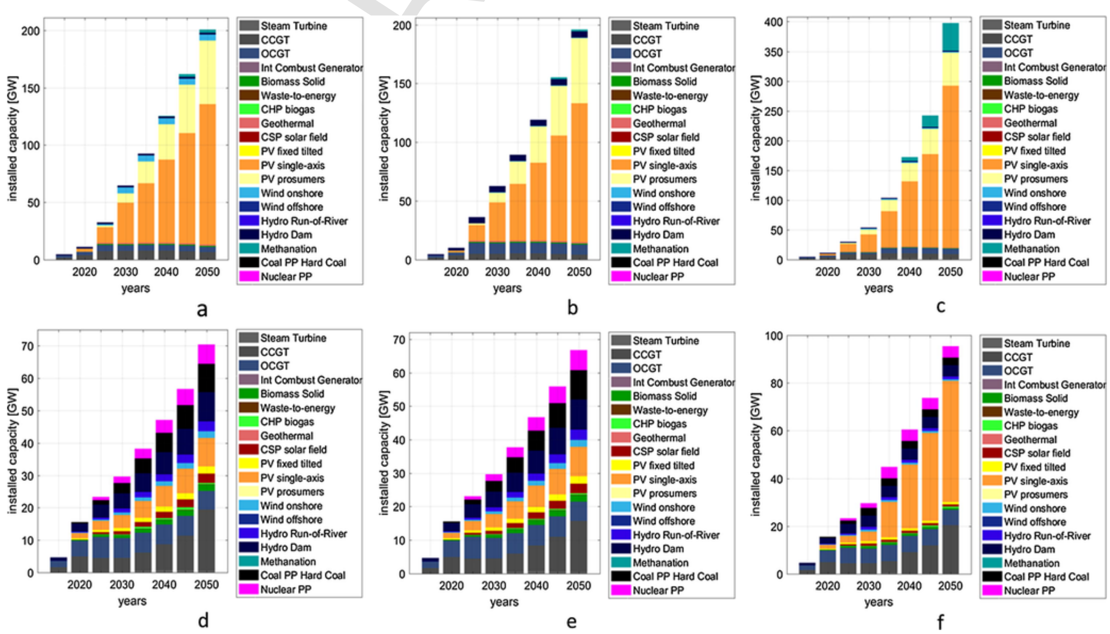

Fig. 11. Cumulative Installed capacity for all generation technologies from 2015 to 2050 for all scenarios.

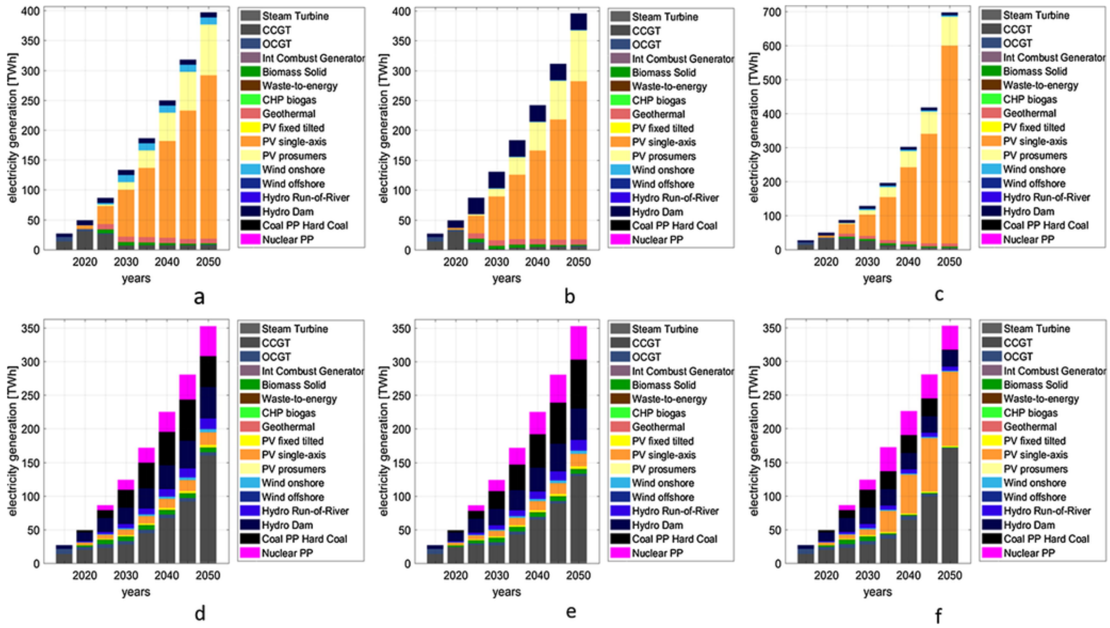

Fig. 12. Total electricity generation by technology from 2015 to 2050 for all scenarios.

Furthermore, the installed capacities in the Current Policy Scenarios are shown in Fig. 11(d)–(f). Gas turbine dominates the Current Policy Scenarios installed capacities during the transition, while coal and nuclear are introduced into the system from 2020 and 2025 onwards, respectively. By 2050, gas turbines dominate except in CPS-3. In CPS-3, after 2030 no new coal is installed, whereas nuclear power plants are allowed to reach 4.8 GW in accordance with the government plan [12]. The model is allowed to decide on new capacity additions for all technologies from 2030 onwards in CPS-3. By 2050, solar PV dominates the power system in CPS-3. The impact of increased RE capacities, particularly single-axis tracking PV, observed in the CPS-3 from 2030 onwards is noticeable. The electricity generation mix in the Current Policy Scenarios during the transition are shown in Fig. 12(d)–(f). By 2050, gas turbines dominate in terms of electricity generation among other thermal power plants in all the Current Policy Scenarios. Whereas, hydropower dominates electricity generation amidst other RE technologies in all the Current Policy Scenarios, except in CPS-3 where solar PV dominates.

A noticeable difference can be observed in terms of capacity requirements in the Best Policy Scenarios and Current Policy Scenarios (Fig. 11). Higher installed capacities are required in all Best Policy Scenarios due to lower full load hours (FLH) of RE technologies, in particular solar PV. The required capacities in the Best Policy Scenarios range from about 198–350 GW, whereas the BPS-3 has the highest share due to additional demand created by desalination and non-energetic industrial gas. Whereas in the Current Policy Scenarios, the capacity requirement ranges from 64 to 95 GW, due to high FLH of thermal generators.

4.3. Annual greenhouse gas emissions in the transition period

The annual GHG emissions during the energy transition period for all the scenarios are presented in Fig. 13. The annual GHG emission reduction trend varies from one scenario to another. In the Best Policy Scenarios, carbon dioxide equivalent (CO_{2eq}) emissions reduce to zero by 2050 as shown in Fig. 13(a)–(c). In the BPS-3, the GHG emissions trend increase until 2030 due to additional electricity generation via fossil gas, to satisfy the demand of non-energetic industrial gas and seawater desalination sectors. While in the Current Policy Scenarios, GHG emissions increase until 2050 as shown in Fig. 13(d)–(f). By 2050, the Nigerian power system is completely decarbonised in all the Best Policy Scenarios.

4.4. Electrical energy storage requirement and utilisation

This section presents the storage portfolio, in terms of capacity expansion and utilisation in the energy transition as shown in Figs. 14 and 15. The storage technologies mix offers additional flexibility to the power system, due to an increased share of limited dispatchable variable renewable energy (VRE) generators in the fully renewable end-point scenarios (Best Policy Scenarios). The storage outputs are 164 TWh, 149 TWh and 179 TWh for BPS-1, BPS-2 and BPS-3, respectively, by 2050, as shown in Fig. 14(a)–(c). The plausible reason for lower storage output in BPS-2 is due to high share of dispatchable hydropower generation. Contrarily, storage output ranges from 15 TWh to 42 TWh in the Current Policy Scenarios by 2050. In addition to the foregoing analysis on storage output, battery storage dominates in all the scenarios, followed by TES, particularly in the Current Policy Scenarios as shown in Fig. 14. TES is important in the Current Policy Scenarios due to CSP installed capacities. The heat generated through CSP and power-to-heat is stored in TES. In addition, higher storage output is observed in CPS-3 in comparison to other Current Policy Scenarios, due to an increased share of solar PV from 2030 onwards. In all the scenarios, the storage outputs increased from 2030 until 2050. Battery storage becomes relevant in the energy transition due to daily charge and discharge, particularly in the Best Policy Scenarios. The high share of PV in the Best Policy Scenarios is reflected in an increase in battery storage utilisation, thus PV-battery systems emerge as the least cost combination in a fully RE powered system for Nigeria. Gas storage utilisation becomes noticeable from 2040 onwards, particularly in the Best Policy Scenarios due to increasing contribution of RE. However, gas storage output is low in comparison to the battery storage output. The reasons are mainly the very low gas storage cycles due to its seasonal characteristic and the gas storage requirement for biomethane, which is accounted for dispatchable RE and not for storing electricity.

Storage capacities required in the Best Policy Scenarios are higher than in the Current Policy Scenarios, as shown in Fig. 15. Gas storage dominates the total installed storage capacities in the Best Policy Scenarios, which is utilised for SNG and bio-methane, but not shown in the storage output diagram, which shows only the Power-to-Gas stor-

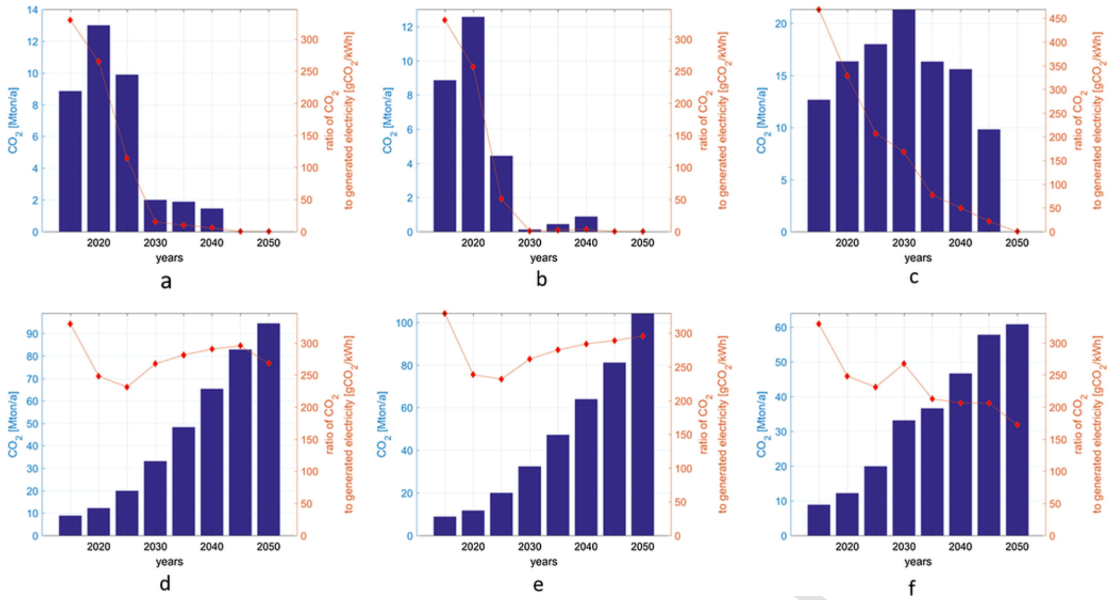

Fig. 13. GHG emissions for all scenarios from 2015 to 2050.

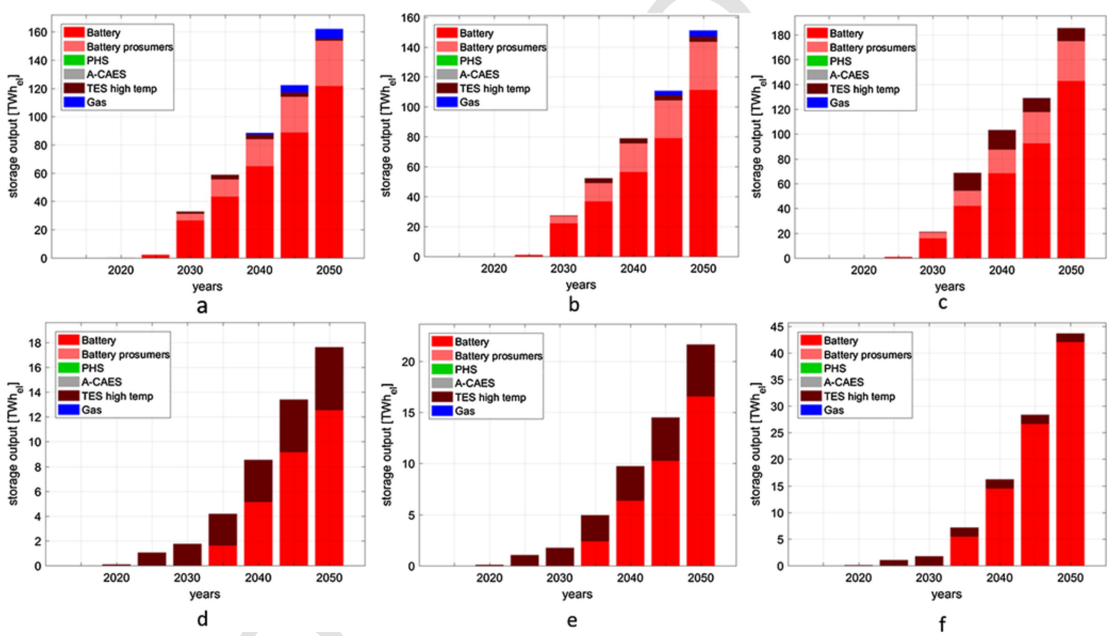

Fig. 14. Storage output of all technologies from 2015 to 2050 for all scenarios.

age. The gas storage reacts in a flexible way to smoothen synoptic and seasonal variations of RE sources. Gas storage capacity becomes more prominent in the Best Policy Scenarios in the year 2045 and 2050 as shown in Fig. 15(a)–(c). In addition, the need for large gas storage capacity is due to replacement of fossil gas with SNG for gas turbines and gas sector demand in particular in BPS-3. In comparison to other Best Policy Scenarios, storage capacity is lower in BPS-2 due to a higher share of hydropower, which serves as virtual storage in this scenario.

Furthermore, the required storage capacities in the Current Policy Scenarios are lower in comparison to the Best Policy Scenarios; plausible reason for this is the increasing share of dispatchable hydropower and fossil-fuelled generators. On the other hand, the storage capacities in the Current Policy Scenarios are dominated by battery storage followed by TES. This study reveals that an increase in VRE shares results in corresponding storage capacity increase, in order to provide the power system with required flexibility. The state of charge of all storage technologies in 2050 are presented in the Supplementary Material (Figs. S7–S12).

Excess renewable electricity goes directly to PtG. However, the battery-to-PtG effect [57] is observed in energy systems of very high renewable energy shares, such as the Best Policy Scenarios, as a means of reducing total system cost. Batteries can be used for supporting the charging of gas storage. This occurrence is visualised in Fig. 16, which shows batteries discharge to the PtG process. When demand is low, mainly at night and early morning hours, energy stored in batteries is discharged to electrolyser units to produce SNG, which is stored for a long term, so that solar electricity of the following daytime can be more effectively stored again in batteries. This optimised system design reduces overall curtailment, reduces PtG charging capacities, increases PtG charging full load hours, and thus reduces the overall energy system cost. This phenomenon does not occur or fairly happen during the rainy season, particularly around June to August. The amount of elec-

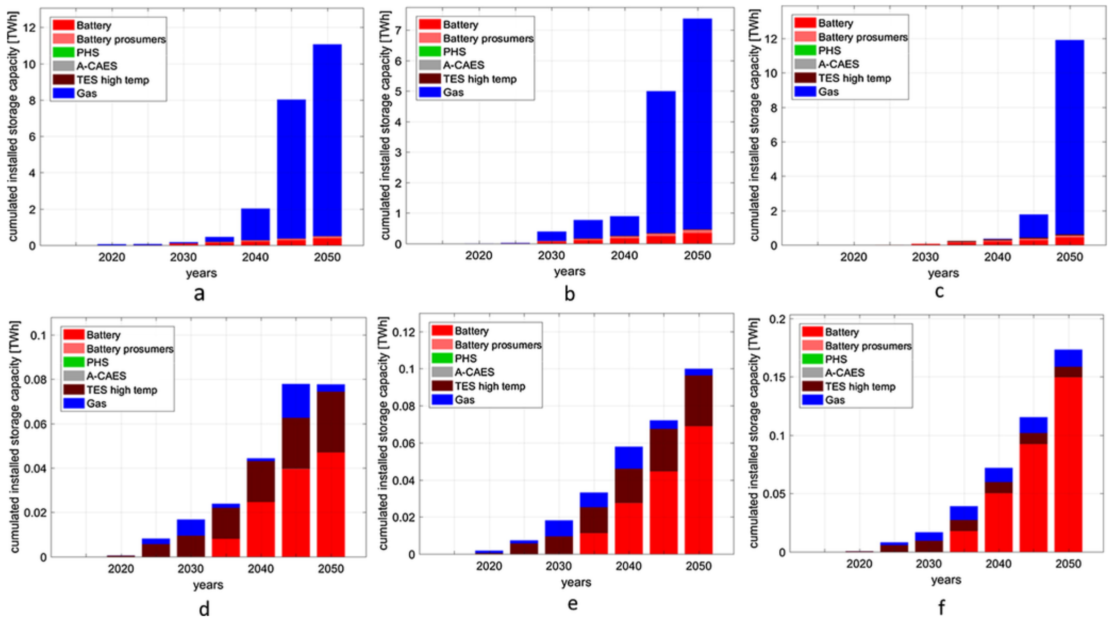

Fig. 15. Cumulative installed capacities of storage technologies from 2015 to 2050 for all scenarios.

Fig. 16. Battery-to-PtG discharge in the BPS-3 scenario for the year 2050.

tricity discharged from batteries to PtG charging are 7 TWh, 4 TWh and 26 TWh in BPS-1, BPS-2 and BPS-3, respectively, representing 2%, 1% and 7% of the electricity demand in 2050. Results of this research show that this phenomenon occurs mainly in the later periods driven by very high PV-battery shares in the energy system.

4.5. Electricity transmission grid utilisation

Integration of VRE resources requires an increase in flexibility. Besides storage technologies, transmission grids provide flexibility to the power system, in shifting of energy from one sub-region to another within the country. Storage provides the flexibility to shift energy from one point in time to another at the same location, whereas transmission grids shift energy from one location to another at the same point in time, hence providing different classes of flexibility. Transmission grids help in balancing electricity supply and demand in various sub-regions. The six sub-regions can be categorised into two: excess-power (or exporting) and deficit-power (or importing) sub-regions. Grid interconnection within the country enhances energy shifting across the country from excess-power to the deficit-power sub-regions. Fig. 17 shows the net electricity transfer between the six sub-regions for the BPS-1 scenario in 2050. The width of the flow indicates the amount of electricity transmitted between the sub-regions. The northern sub-regions are the main exporting regions, especially the NIG-NW region exports huge amounts of electricity of about 200 TWh in BPS-1 by 2050. While the southern sub-regions are the importing regions, in particular

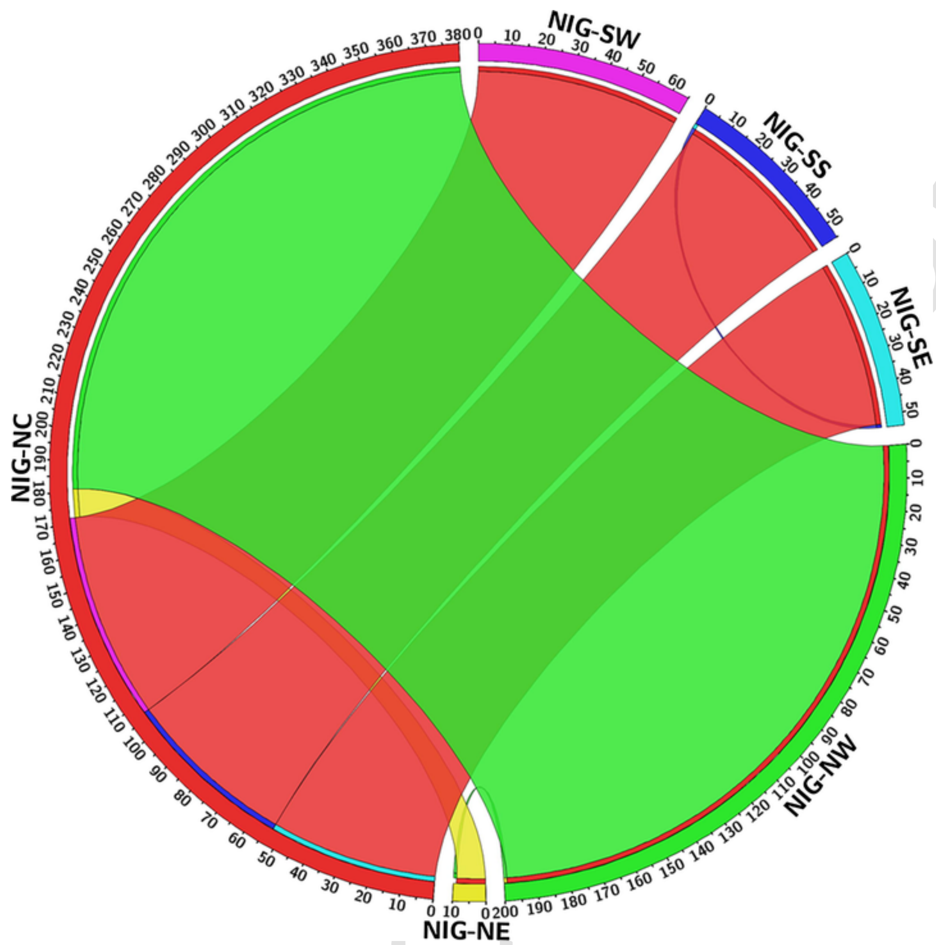

Fig. 17. Electricity exchange across Nigeria in 2050 in the Best Policy Scenario 1.

the NIG-SW sub-region. The plausible reason for huge exports from the northern sub-region is the excellent solar resource in the region and low cost of PV, since the LCOE is about 17% lower than in the main importing regions due to about 21% higher FLH. The grid utilisation increased with the penetration of RE from 2020 onwards. The net grid export between the sub-regions in the Best Policy Scenarios 1, 2 and 3 are 204, 214 and 371 TWh in 2050, respectively. While the net electricity exchange in the Current Policy Scenarios ranges from 14 TWh to 46 TWh in 2050. This research shows that an increase in spatial-temporal generation of RE, particularly solar PV and wind, requires a powerful high voltage grid for smoothening fluctuations and gaining access to sub-regions with the highest resource potentials. Grid utilisation for all the scenarios in 2050 are presented in the Supplementary Material (Fig. S12).

4.6. The role of gas turbines in the energy transition

Besides the outstanding role of storage technologies and the transmission grid, gas turbines also provide additional flexibility to the power system. Gas turbines are found to be a valuable and flexible balancing technology in the energy transition based on the timescale of the variation they cover, from days to months. In addition, gas turbines are allowed to be installed after 2015, due to lower GHG emissions and the possibility to substitute fossil gas with SNG or biomethane. The average FLH of gas turbines decrease from 5940 in 2015 to 668 in 2050, for the BPS-1. Similarly, the average FLH of gas turbines decline to 380 in the BPS-2, whereas the FLH decrease in the BPS-3 to almost zero, since balancing with electrolysers as a major demand response option is lower in cost. By 2050, the total dispatchable installed gas turbine capacities are 10 GW, 12 GW, and 16 GW in BPS-1, BPS-2 and BPS-3, respectively. The gas turbine generation is 7.0 TWh, 4.7 TWh and 0.02 TWh in BPS-1, BPS-2 and BPS-3, respectively, by 2050. The demand response potential of electrolysers in 2050 is documented by the installed power input capacities of 7.0 GW, 4.6 GW, and 137.1 GW in the BPS-1, BPS-2 and BPS-3, respectively.

4.7. Analysis of sub-region installed capacities in a fully renewable energy system

This section presents a more detailed view of installed capacities for a fully RE-based energy system in 2050 for the six sub-regions, as presented in Fig. 18. The Best Policy Scenarios 1 and 3 are selected for this analysis. A noticeable difference can be seen between the BPS-1 (Power only scenario) and BPS-3 (Integrated scenario) in terms of capacity requirements. The total capacity required is 198 GW and 351 GW in BPS-1 and BPS-3, respectively. Solar PV dominates the total installed capacities, in particular PV single-axis tracking. PV single-axis tracking accounts for 60% and 78% of the total installed capacities in BPS-1 and BPS-3, respectively. The role of PV prosumers are also observed in both scenarios. In BPS-3, seawater desalination and SNG production are integrated into the power system, which increases the electricity demand substantially. The additional capacity requirement due to sector coupling was supplied by solar PV, mainly PV single axis tracking. By 2050, solar PV emerges as the most relevant technology and the cheapest source of electricity for the Nigerian power system. The plausible reason for this is due to the country's location within the Sun Belt, where solar resources are fairly well distributed. However, the intensity of solar radiation exhibits significant disparity from south

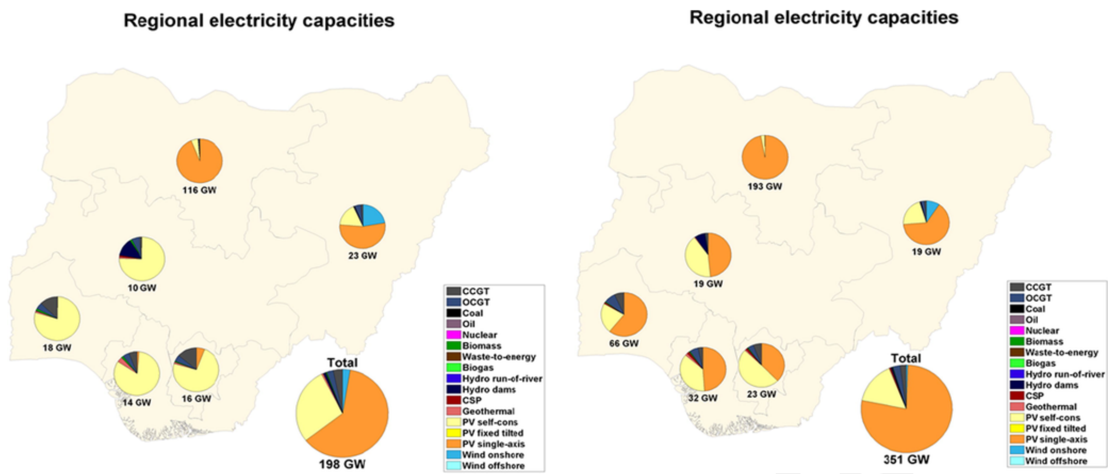

Fig. 18. Installed RE capacities for Best Policy Scenario 1 (left) and Best Policy Scenario 3 (right) for the six sub-regions of Nigeria in 2050.

to north. The solar PV potential is the highest in the northern sub-region, resulting in a high share of PV capacity, particularly in NIG-NE and NIG-NW. Solar PV dominates the energy system, and is complemented by wind, hydropower, geothermal and biomass. The northern sub-regions are exporting regions due to excellent resource availability. More graphical results on regional electricity capacity and generation for each scenario in 2050 can be found in the Supplementary Material (Figs. S14–S15).

4.8. Integrated scenario – best policy scenario 3 (desalination and industrial gas sector)

This scenario integrates seawater desalination and non-energetic industrial gas sectors into the power system. The overall LCOE and capacity requirements for this scenario have been analysed in previous sections. The desalination demand for Nigeria is calculated according to [54]. Desalination demand in the country is low and remains stable at 10,344 m^3/day from 2015 until 2050, most of the demand occurs in NIG-NW and NIG-NE. According to the results of this research, the levelised cost of water (LCOW) is 0.6 €/m^3 in 2050. The LCOW and installed capacity from 2015 until 2050 are shown in Fig. 19. The LCOW includes also the water transport cost from seawater desalination sites to the sites of demand. The total electricity demand from the desalination sector is 0.02 TWh_{el} in 2050.

The total gas demand increases from 60 TWh in 2015 to 185 TWh in 2050. Fig. 20 shows the total gas demand and input by source from 2015 until 2050. Gas demand in the power sector increases until 2030. Afterwards, it begins to decline due to strong RE growth. While the gas demand in the industrial sector increases until 2050. The total annual capital expenditures in the gas sector increase from 0.4 b€ in 2015 to 19.8 b€ in 2050. The total electricity demand in the gas sector is 290 TWh_{el} in 2050.

Fossil natural gas shows a strong influence on the energy system, which is subsequently replaced with SNG during the transition. The SNG production increases in the system from 2040 onwards, and completely replaces fossil-based fuel in 2050. Fig. 21 shows the hourly resolution of the state of charge of gas storage and the operation of methanation units in 2050. SNG production occurs during the daytime almost throughout the year, due to excellent PV conditions in the country. The flexibility of PtG units is lower in cost than battery storage, since otherwise the PtG units would be run also during the night hours, utilising battery storage. The gas storage reaches the peak of charge around April to June, and starts to continuously discharge around July to September, which is the rainy season in Nigeria. Industrial gas demand is nearly constant throughout the year. During the raining season, when SNG production is low or is not available at all, gas storage is discharged to meet the gas demand.

Figs. 22 and 23 present the hourly generation for a sub-region in the north (NIG-NE) and south (NIG-SW). A 2-week period is selected which shows hourly generation during the Harmattan in NIG-NE (Fig. 22) and rainy week in NIG-SW (Fig. 23). The hourly generation in NIG-NE is influenced by the Harmattan season that is characterised by prevailing northeasterly wind conditions that blow from the Sahara Desert over West Africa into the Gulf of Guinea between the end of November and the middle of March, with good solar conditions. This results in remarkable generation from solar PV and wind, while the battery units

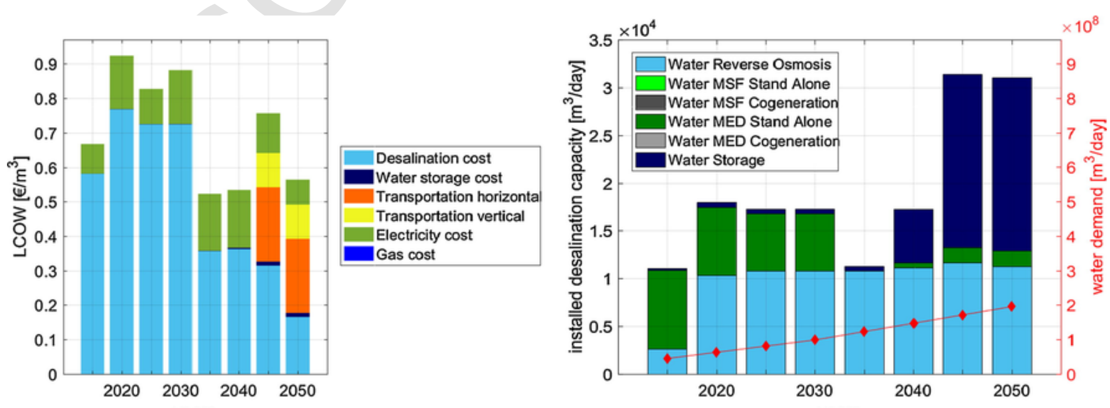

Fig. 19. LCOW components (left) and installed desalination capacities (right) from 2015 to 2050.

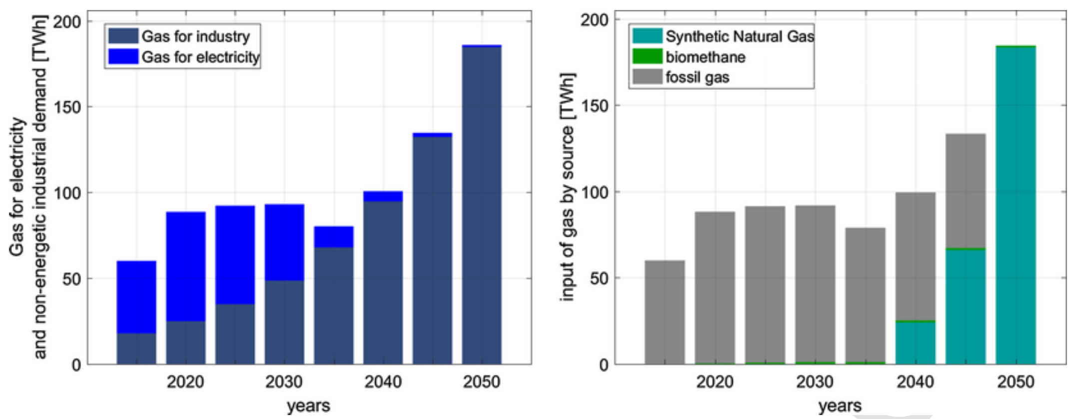

Fig. 20. Total gas demand (left) and gas input by source (right) from 2015 until 2050.

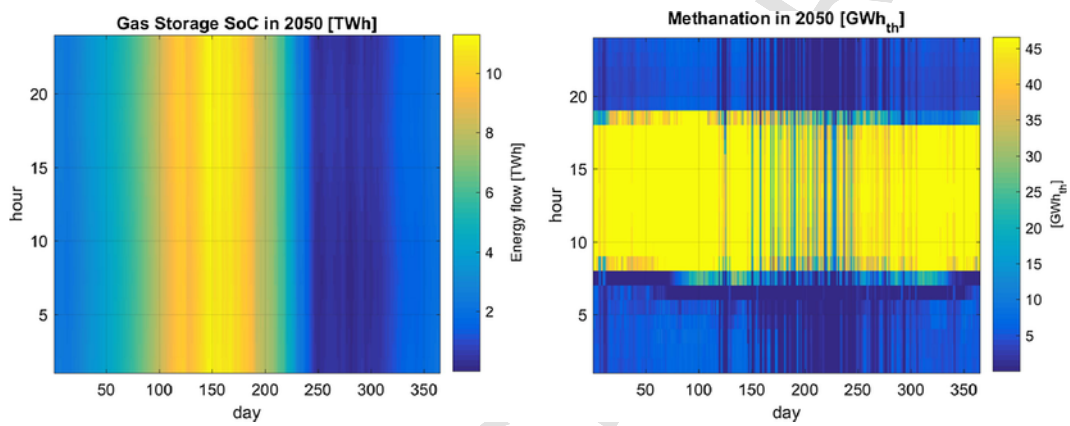

Fig. 21. Hourly resolution of state of charge of gas storage and production of methanation units in 2050.

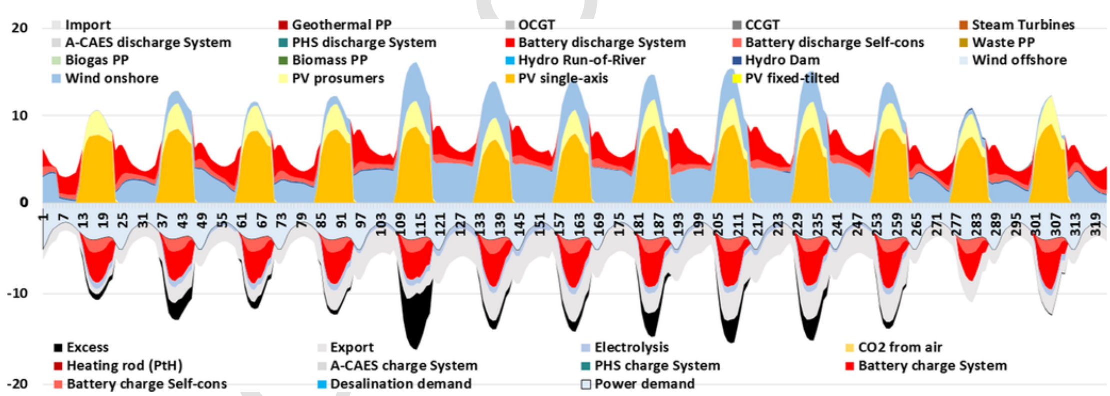

Fig. 22. Electricity generation and demand profile in full hourly resolution for the Best Policy Scenario 1 for the NIG-NE in 2050.

are discharged during the night hours as shown in Fig. 22. Fig. 23 presents the hourly generation profile in NIG-SW during a week in the rainy season. During this week the role of gas turbines is observed in providing flexibility to the power system due to low generation from RE. However, PV prosumers, electricity imports and battery discharge during night hours have a substantial influence in this sub-region.

Fig. 24 shows the energy flow in the Best Policy Scenario 3 (Integrated scenario). It shows the RE generators, storage technologies, transmission grids, total electricity demand for each sector and system losses. The potential usable heat and system losses include the difference between the electricity generation and final electricity demand. Both includes curtailed electricity, the heat released from biomass, biogas and waste-to-energy power plants, charge and discharge from storage technologies, electrolysers and methanation processes. Solar PV meets additional demand due to sector coupling in the Integrated scenario.

4.9. Comparison of key differences in all scenarios by 2050

This section presents key differences in all scenarios examined by 2050 as presented in Table 2. The total annualised cost of system trajectory from 2015 to 2050 is shown in Fig. 25. The modelled financial outcomes reveal that a fully decarbonised energy system is the least cost option for Nigeria. The total annualised cost of system for all Current Policy Scenarios are higher than in the Best Policy Scenarios, except in the BPS-3 due to sector coupling. The average total annualised cost of system in all Current Policy Scenarios are 42% higher than in Best Policy Scenarios. The total annualised cost of system ranges from

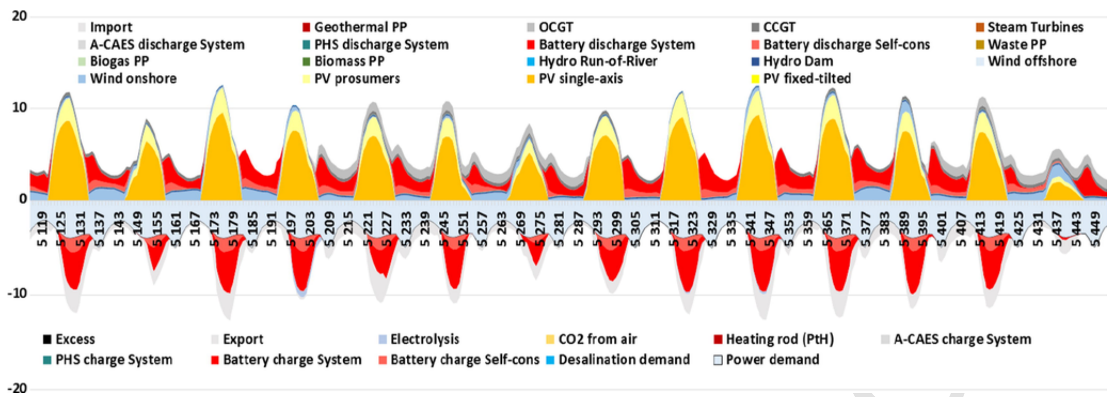

Fig. 23. Electricity generation and demand profile in full hourly resolution for the Best Policy scenario 1 for the NIG-SW in 2050.

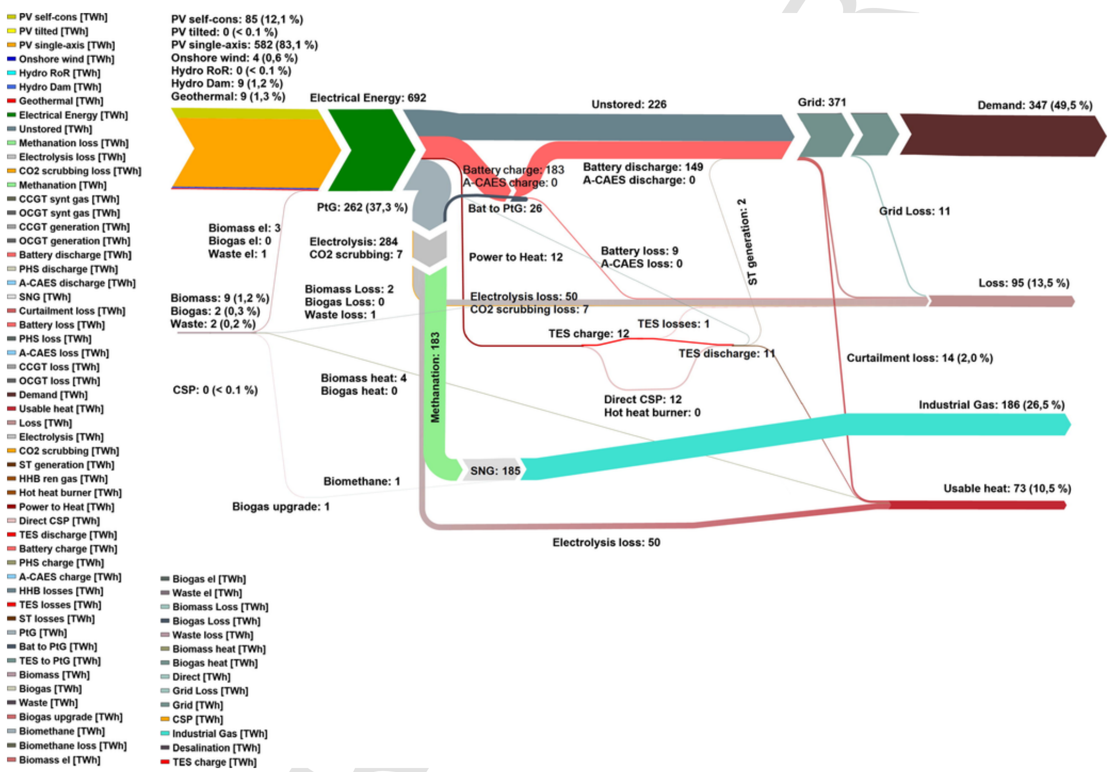

Fig. 24. Energy flow of the system for the Integrated scenario in 2050.

Table 2
Difference in key parameters and financial outcomes in 2050 for all scenarios.

			BPS-1	BPS-2	BPS-3	BPS-1noCC	BPS-2noCC	CPS-1	CPS-2	CPS-3
Financial outcome	Total annualised cost of system	[b€]	16.6	15.8	27.2	16.2	15.5	42.2	26.4	35.0
	LCOE	[€/MWh$_{el}$]	48	46	35	47	45	120	76	100
Electricity parameter	Demand	[TWh$_{el}$]	347	347	637	347	347	347	347	347
	Generation	[TWh$_{el}$]	398	396	697	395	383	353	353	353
	Installed capacity	[GW]	198	194	351	192	190	68	64	95

15 to 42 b€ in all the scenarios. The LCOE obtained in the Current Policy Scenarios are higher than in the Best Policy Scenarios. The LCOE is found to be in the range of 34.5–120.4 €/MWh. The capacity requirements are higher in the Best Policy Scenarios than in the Current Policy Scenarios. This is due to lower FLH of solar PV that dominates the overall capacities in Best Policy Scenarios, while the Current Policy Scenarios are dominated by thermal generators that run on higher FLH. On average, capacity requirements in all Best Policy Scenarios are about 70% higher than in the Current Policy Scenarios. Higher generation is observed in the Best Policy Scenarios than in the Current Policy Scenarios.

Furthermore, the Best Policy Scenario 1 no GHG emission cost (BPS-1noCC) and the Best Policy Scenario 2 no GHG emission cost (BPS-2noCC) are examined in this research. The Best Policy Scenario no GHG emission cost modelling outcome reveals that a RE-based energy system would yet be more competitive in the mid-term future in Nigeria. By 2050, RE electricity generation reaches 97.8% of total electricity generation in BPS-1noCC and BPS-2noCC. In both scenarios as

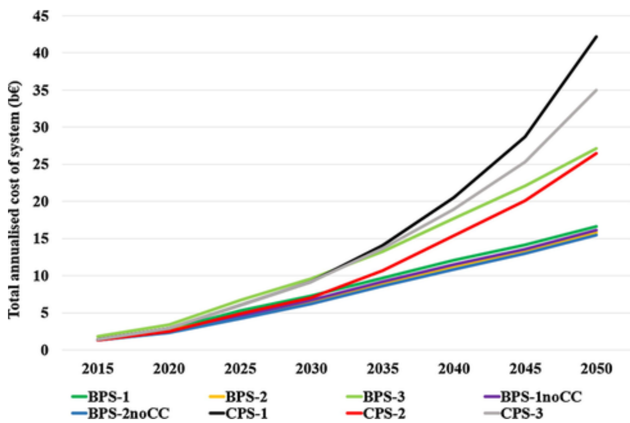

Fig. 25. Comparison of total annualised cost of system for all scenarios in 2050.

GHG emission cost is not applied, natural gas is allowed to be used in gas turbines. However, the RE installed capacities slightly drop in both scenarios, due to increased FLH of gas turbines. The total annualised cost of system and LCOE decrease slightly in BPS-1noCC and BPS-2noCC as GHG emission cost is assumed to be zero throughout the transition for both scenarios as shown in Table 2. Additional information on these scenarios are available in the Supplementary Material (Tables S11–S12, S22–S23, S30–S32 and Figs. S16–S19).

5. Discussion

This study presents pathways of transitioning to a zero GHG emission energy system for Nigeria under the defined scenarios. The key objectives of this research is to show that a fully sustainable energy system is technically and economically feasible and the respective financial consequences in comparison to a fossil-based power system. Such an energy system can be achieved with abundant RE resource availability in the country, enabled by strong political support for renewable energy development.

A 100% RE-based energy system is achievable in Nigeria. This study is the first of its kind to be conducted for Nigeria. The LCOE values obtained in this study indicate that cost of electricity could decrease from 54 €/MWh in 2015 to 46 €/MWh in BPS-1, 48 €/MWh in BPS-2 and 35 €/MWh in BPS-3 by 2050. Whereas in the Current Policy Scenarios, the LCOE increased from 54 €/MWh in 2015 to 120 €/MWh in CPS-1, and 100 €/MWh in CPS-3 by 2050. However, the LCOE obtained by the no GHG emission cost scenarios declined from 51 €/MWh in 2015 to 47 €/MWh in BPS-1noCC, 45 €/MWh in BPS-2noCC and 76 €/MWh in CPS-2 by 2050. Results obtained in the fully renewable end-point scenarios for Nigeria in terms of LCOE are comparable to the global average LCOE obtained using the LUT model, which shows a range of about 50–70 €/MWh [22]. The decreasing costs of RE technologies expected during the transition, particularly solar PV, contributes to the decreasing cost of electricity over the transition in the Best Policy Scenarios. In addition, sector coupling of seawater desalination, non-energetic industrial gas and electricity demand results in a further reduction in LCOE by 22% in 2050 as observed in BPS-3. Sector coupling provides additional flexibility to the power system. In addition, a higher share of low-cost generation leads to the LCOE reduction. The additional demand required due to sector coupling is mainly satisfied by installation of low-cost solar PV. PtG technology enables the coverage of gas demand for the integrated scenario (BPS-3) creating additional electricity demand of 290 TWh_{el} in the year 2050, which results in increased generation capacity.

The outstanding role of PV technologies and batteries needs to be highlighted in the fully renewable end-point scenarios in Nigeria. By 2050, PV single-axis tracking dominates the system in the Best Policy Scenarios. While the rest of the PV capacity is met by PV prosumers. Prosumers contribute 22% of total generated PV electricity in 2050. PV-battery prosumers will reduce dependency on the centralised system in the nearest future in Nigeria according to the results of this research. In comparison to the Current Policy Scenarios, PV capacity range from 11 GW to 52 GW in 2050, the highest share of PV installed capacity is observed in the CPS-3. By 2050, PV technologies generate 364 TWh (93% of total generation), 350 TWh (89%) and 667 TWh (96%) in BPS-1, BPS-2 and BPS-3, respectively. The increased generation in BPS-3 is due to demand of three energy sectors. Whereas in the Current Policy Scenarios, PV generation ranged from 22 TWh to 112 TWh, accounting for 6–32% of the total electricity generation in 2050. The highest installed PV capacities were found in the northern sub-regions in particular the NIG-NW and NIG-NE, due to excellent solar resource conditions in the north of Nigeria and respective low cost of PV technology. In addition to the foregoing analysis, solar PV technology will play a major role in the Nigeria future power system, based on the results of this research and from resource point of view as discussed in [58]. Most studies on future energy systems in Nigeria have attempted to analyse renewables potential in meeting the growing electricity demand of the country [8], but did not investigate what this may mean in concrete power generation mix options. Brimmo et al. [59] provided an in-depth review on wind, hydropower, geothermal and nuclear energy options in Nigeria. Solar energy resource current application and the extent of utilisation is presented in [58], while Akuru et al. [7] based on literature, modeled scenarios and field experience conclude that 100% RE in Nigeria could be driven by individuals rather than sole dependence on government actions. The rest of the generation is supplied by wind energy, hydropower, geothermal and biomass in the 100% RE-based scenarios considered in this research. In the BPS-2, hydropower projects under construction such as Mambilla hydropower project in Taraba State and Zungeru hydropower project in Niger State were considered. Hydropower has been a major part of the Nigerian power fleet. The Government of Nigeria also plans to build more hydropower capacity in the nearest future. Increased hydropower capacity is one marked feature of the BPS-2. However, dispatchable hydropower contributes to lower storage needed in BPS-2. By 2050, hydropower capacity is 1.7 GW in BPS-1 and BPS-3, while it reaches 5.3 GW in BPS-2. The hydropower installed capacity is 12.1 GW each in CPS-1 and CPS-2, while installed capacity reaches 5.9 GW in CPS-3 in 2050. According to IEA New Policy Scenario, hydropower capacity is expected to increase from 2 GW (11%) in 2012 to 15 GW (19%) in 2040 [6]. The high share of hydropower in BPS-2 results in lower LCOE and storage requirement, as hydro reservoirs serves as virtual storage [60]. One of the main constraints of hydropower development is cost overruns and schedule spills [14], especially large hydropower projects [15]. According to [16], 61 hydropower dams were analysed representing 114 GW and 271.5 bUSD worth of investment experienced a mean cost overrun of 231 bUSD [16]. These projects exhibited a mean cost overrun of 70% [16]. Another study reports an average 96% cost overrun on hydropower development, where the authors report that the cost overruns figures exclude inflation, debt, environmental cost and social cost [61].

The specific capacity density derived in the LUT Energy System model is 75 MW/km^2 for optimally tilted PV and 8.4 MW/km^2 for onshore wind in [20]. Hence, the total area of land required in Nigeria for solar PV and wind capacities in 2050 is 2409 km^2 (0.3% of total land area) and 361 km^2 (0.04%) for BPS-1, 2317 km^2 (0.3%) and 53 km^2 (0.01%) for BPS-2, and 4369 km^2 (0.5%) and 209 km^2 (0.02%) for BPS-3. The land area requirement for achieving a 100% RE system should be no limiting factor, according to the results of this research.

Furthermore, there are plans underway in Nigeria to build new thermal power plants [19], mainly nuclear and coal power plants [12]. The Current Policy Scenarios are mainly dominated by thermal plants, which include gas turbines, nuclear and coal power plants. In 2017, the Nigerian government signed a multi-billion dollar contract with

Rosatom, a Russian nuclear company to build four nuclear plants in Akwa Ibom and Kogi State to contribute 4.8 GW to Nigerian electricity by the year 2035 [62]. In 2000, Rosatom estimated cost to build two new pressurised water reactors of the VVER series at the Leningrad nuclear power plant 2 at 1.74 b€ for 2.17 GW. By 2011, Rosatom set price for this type of project was estimated at 3.73 b€, more than twice the original price [63]. The cost of Olkiluoto 3, Finland, which was planned to begin operation in 2009, have increased from 3.2 b€ to 8.5 b€ for 1.6 GW, and stand the risk of further cost increase [64]. Countries like Nigeria should be aware of binding nuclear contracts, similar to the contract signed in 2014 by the Hungarian government with Rosatom, incurred financial burden is always borne by the foreign government. Rosatom nuclear construction projects within Russia and other countries have not been characterised by delays and cost overruns, but also by lack of proper quality control and safety concerns [63]. Sovacool et al. [16] analysed 401 power plant projects in 57 countries, thereof 180 nuclear reactors representing 177 GW. These reactors had a mean cost overrun of 117%, and more than 9 in 10 projects suffered from cost escalation [16]. In addition, nuclear energy violates all sustainability criteria that should form a framework for a resilient energy system design discussed in [13]. Various risks are associated with nuclear energy [65], which includes environmental and health risks as witnessed in Fukushima and Chernobyl, irreparable impact on ecosystem resulting from genetic mutation plants and animals, and risk of nuclear weapons proliferation and potential terrorist attacks on nuclear facilities [13]. The Current Policy Scenarios are observed to be expensive due to high capital costs of thermal plants in particular nuclear. According to [66], the LCOE median values ranged from 79 to 112 €MWh, and LCOE including external and GHG emission cost ranged from 87 to 120 €/MWh [67]. Rather than building new nuclear and coal power plants in Nigeria, gas turbines (OCGT and CCGT) could be an option alongside with new investments in RE technologies in particular solar PV. In all the scenarios, gas power plants emerge as the dominant thermal power plant, particularly in the Current Policy Scenarios. The result obtained in the Current Policy Scenarios, is comparable to the findings of the IEA New Policy Scenario, which reports gas-fired generation will form the core of the Nigerian future power sector [6]. According to IEA [6], gas power plant capacity may be 37 GW (48%) and coal may be 8 GW (10%) by 2040. Similarly, according to the IRENA Renewable Promotion scenario about 55% electricity generation is supplied by gas power plant, hydropower supply is about 35% and remaining share is supplied by imports for the year 2030 [68]. In the Best Policy Scenarios, gas power plants are used as a very valuable and flexible balancing technology on different time scales, from days to weeks. Gas turbines can be installed after 2015, because of lower GHG emissions and the possibility to substitute the fossil natural gas with SNG or biomethane.

Storage technologies play a vital role in this study, particularly in the Best Policy Scenarios due to high shares of RE resources. Solar PV dominated power grids are usually characterised by high storage requirements [69]. In this research, high penetration RE source, in particular solar PV, is complemented by battery storage due to daily requirement. The PV-battery hybrid system emerges to become the least cost solution in a 100% RE-based powers system by 2050. In addition, the cost of batteries declined by 80% in the past 6 years [70], further cost reduction is expected [71], policies designed to strengthen market growth and innovation in battery storage can drive the future cost reduction [72]. The continued cost decline of PV-battery systems [22] combined with excellent solar resources in Nigeria are the key drivers for a high share of PV in all the Best Policy Scenarios. By 2050, battery storage output in the Best Policy Scenarios ranged from 157 TWh to 166 TWh and from 13 TWh to 42 TWh in the Current Policy Scenarios. The plausible reason for low storage output and requirement in the Current Policy Scenarios is due to higher share of dispatchable hydropower and thermal power plants. Additional battery storage demand of 106 GWh is projected in 2050 because of higher PV prosumers installed capacity. The battery prosumers output increased from 0.2 TWh in 2025 to 32.1 TWh in 2050. In terms of storage capacity, gas storage dominates in the Best Policy Scenarios, while battery storage dominates in the Current Policy Scenarios, followed by TES. The technology requirement in the Best Policy Scenarios are higher than in the Current Policy Scenarios, due to lower FLH of RE in particular solar PV and strict constraints on fossil fuel. The high gas storage capacity is required for PtG and gas turbines, as fossil natural gas is replaced by SNG. According to Fasihi et al. [73], RE-based synthetic fuels are a real option for decarbonising the power system for the year 2030 and beyond.

The role of power grids becomes prominent from 2020 onwards, and utilisation increases with penetration of RE shares in the power system, particularly in the Best Policy Scenarios. The grid interconnection enhances the shifting of energy from exporting sub-regions with high renewable resource potentials to the importing sub-regions. According to the results of this study, transmission grids are vital in reaching a fully sustainable power system in Nigeria by 2050. Brown et al. [21] show that sector coupling, together with electricity transmission networks, can reduce the total system costs by up to 37% compared to a system with none of these flexibility options. However, a mix of several flexibility options such as long- and short-term energy storage, district heating and synthetic fuels are found to be more beneficial than power transmission alone. Investments in grid expansion are vital to the development of the Nigerian power system. According to the IEA New Policy Scenario, the rate of electricity access is expected to increase from 45% in 2012 to around 85% in 2040 through grid extension due to high population density and widespread network coverage in the country [6]. However, grid extension is often a time-consuming process, which might leave many people without electricity for a long period [74]. The grid extension approach has not contributed significantly to an eradication of energy poverty in many SSA countries, including Nigeria [75]. Thus, off-grid solutions based on RE technology, particularly solar PV based technologies (solar home systems (SHS) and mini-grids), provide solutions in areas where grid extension is not cost-effective [76]. According to Bertheau et al. [77], two scenarios were modelled to understand the effects on future grid extension plans in SSA. Results of the modelling reveals that about 96 million Nigerians are un-electrified. In the first scenario based on the existing grid, 22.1 million people (23%), 38.5 million people (40%) and 35.6 million people (37%) can be electrified by mini-grids, grid extension and solar home systems, respectively. The second scenario, in which modelling was based on the planned grid, 17.3 million people (18%), 51 million people (53%) and 27.9 million people (29%) can be electrified by mini-grids, grid extension and SHSs, respectively [77]. Furthermore, SHS can serve as short-term solution until grid connection can be achieved or economic power makes the establishment of mini-grid feasible [78]. Accelerating electrification access requires in depth spatial and techno-economic analysis in identifying least cost and optimal electrification mix options in rural areas [79]. Ouedraogo [80] highlights that the electrification rate in SSA has to be increased 40-fold from today's electrification level to decrease the electricity poverty in the continent. This can be achieved by an increase of new RE-based power generation capacity and off-grid systems.

Furthermore, the water sector is fundamental to the country's development, and the government of Nigeria has made provision for water and basic sanitation the responsibility of the Federal Ministry of Water Resources (FMWR) [81]. Water availability varies across the country. According to [81], Nigeria North-West and North-East are the main regions with water scarcity. In the aforementioned regions, political and economic problems hinder water services. The Nigerian government is committed to providing water coverage to 9 million people yearly beginning from 2016 until 2030. The estimated investment requirement is 378 m€/year, based on United Nation (UN) connection price of 42 €/person to the water network. The nominal tariff charged by the State Water Agency (SWA) ranged from 1.26 to 1.68 € per family per month. Water supply from alternative providers ranges from 5.0 to 6.7 €/m^3 in the North, while prices range from 1.7 to 3.4 €/m^3 in the South [81]. According to the results of this research, LCOW declines from 0.66 €/m^3 in 2015 to 0.56 €/m^3 in 2050. The capex required in 2050 to meet the Nigerian water demand is 14.7 m€, whereas the annual opex fixed and variable is 1.1 m€ and 1.8 m€, respectively.

The results obtained are comparable to the findings of Barasa et al. [5] for the SSA region based on overnight approach for the year 2030, which conclude that SSA countries will be powered mainly by solar PV and complemented by wind energy. In addition, the LCOE obtained in the Best Policy Scenarios are comparable to the LCOE obtained in [5]. Examining the application of a carbon price during the transition, particularly in the Best Policy Scenarios, led to a rapid transition and fast GHG emissions reduction in comparison to no GHG emission cost scenarios. However, the no GHG emission cost scenarios achieved comparable results in terms of capacity, generation, costs of electricity and GHG emission trajectory to the Best Policy Scenarios. By 2050, the RE electricity generation reaches 97.8% in the no GHG emission cost scenarios, with about 2% energy supplied by fossil gas. This indicates that Nigeria's energy transition is achievable without GHG emission cost implementation. The results of this research is fully in line with the recent agreement of several African cities, such as Lagos in Nigeria, Cape Town and Johannesburg in South Africa and Accra in Ghana, to cut carbon emissions to zero until 2050 [82]. An energy system optimisation analysis for the University of Ilorin in Nigeria under several configurations show that a hybrid PV-Diesel-Battery system is the best solution to reduce the GHG emissions cost significantly, while the system costs are also the lowest compared to other configurations [83]. However, the capital cost of solar PV assumed is much higher than the current cost in Nigeria [84]. If the actual cost of solar PV was considered, it is likely that hybrid PV-Battery systems will offer the least cost, while wind energy can also complement. Akuru et al. [7] conclude that 100% RE is possible in Nigeria with the country's abundant RE resources, but that the right government backing is lacking. Though the role of the government cannot be compromised, individuals could drive the transition to 100% RE in Nigeria by installing RE systems in mega cities like Lagos, Abuja or Port Harcourt [7].

6. Conclusion and policy implications

Transition to a carbon-neutral energy system in Nigeria will require a strong political commitment at all levels of governance. Beyond technical feasibility and economic viability of an energy transition towards a zero GHG emission system, it encompasses long-term and well-designed policy interventions. A concerted and consistent policy action that would restrict new investments in fossil power plants, and facilitate RE development in a long-term perspective is exigent for the transition in Nigeria. This research offers key insights to energy system planners and policymakers in Nigeria, and demonstrates the need for a detailed analysis in determining knowledge gaps in transition pathway options under various policy constraints for developing countries of comparable climates. The results of this research demonstrate that a decarbonised energy system is quite competitive in all Best Policy Scenarios in comparison to the Current Policy Scenarios. The high competitiveness is based on an increasing share of RE technologies, particularly the high cost competitiveness of solar PV and supporting batteries. Solar PV dominates all the Best Policy Scenarios by 2050, where PV single-axis tracking contributes the most (63–83%) to the total PV installed capacities followed by PV prosumers. The high shares of PV in the Best Policy Scenarios are reflected in an increase in battery storage utilisation. The combination of solar PV and battery storage was found to be very beneficial for the power system. The need for electricity storage in the energy system is a key characteristic for high penetration levels of VRE. Short-term (Li-ion), medium-term (TES), and long-term (gas storage) storage are required to balance daily, weekly and seasonal variability of RE. Furthermore, energy storage provides flexibility to the energy system by enabling demand balancing. Grid interconnection within the country allows shifting of electricity from one point in time to another, enabling large-scale generation and demand balancing between the different sub-regions. Moreover, gas turbines provide additional flexibility to the power system, where fossil gas is substituted with SNG or biomethane from 2015 onwards in the Best Policy Scenarios. The produced gas can be either used in the power sector to balance the system when it is needed, or stored in gas storage to meet the demand of non-energetic industrial gas sector.

Energy policy in Nigeria should place solar PV at its core. The current perspective of RE utilisation, possible motivation for RE development, barriers and challenges in Nigeria require deliberate actions and strong political will. From a policy perspective, this research identifies investment requirements, timing and operations across Nigeria. Such information are relevant for policy makers and energy planners in Nigeria for setting energy investment targets. During the transition, solar PV and batteries emerge as the most important technologies, complemented by wind energy and existing hydropower. In addition, gas turbines provide flexibility to the power system. A 100% RE-based system is reachable and is the real policy option for Nigeria. RE resources can meet the electricity demand of the power, seawater desalination and non-energetic industrial gas sectors. Furthermore, based on all scenarios examined in this study, the Best Policy Scenarios present the least cost electricity pathways for Nigeria in comparison with the Current Policy Scenarios. The LCOE ranges from 34 to 48 €/MWh for the Best Policy Scenarios, whereas the LCOE for the Current Policy Scenarios lie between 75 and 120 €/MWh. The Current Policy Scenarios clearly demonstrate the need for a cleaner energy system, as a fossil dominated system violates all sustainability criteria. New investments in nuclear power plants in Nigeria are not competitive and show a high risk profile, leading to low social acceptance.

Finally, a well designed RE roadmap, an attractive environment for local and foreign investors, electricity market reforms, research and development and other emissions abatement policies would be required to drive RE development in Nigeria. Innovative financing mechanisms advancing RE development elsewhere in the world can be adopted in Nigeria as well. Further research will be conducted, incorporating other energy sectors (e.g. transport and heat sector) for a wider analysis of the energy transition in Nigeria in the future.

Acknowledgements

The authors gratefully recognize the governmental financing of Tekes (Finnish Funding Agency for Innovation) for the 'Neo-Carbon Energy' projects under the number 40101/14. Ayobami Solomon Oyewo would like to thank LUT Foundation for the valuable scholarship.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enconman.2018.10.036.

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