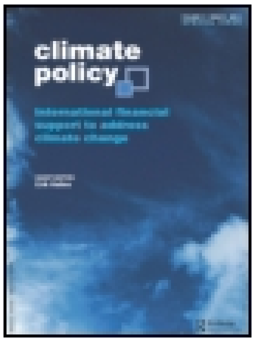

Climate Policy

ISSN: 1469-3062 (Print) 1752-7457 (Online) Journal homepage: https://www.tandfonline.com/loi/tcpo20

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CLIMATE POLICY
https://doi.org/10.1080/14693062.2019.1661818

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Achieving Sustainable Development Goals in Nigeria's power sector: assessment of transition pathways

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ABSTRACT

Nigeria is Africa's largest economy and home to approximately 10% of the un-electrified population of Sub-Saharan Africa. In 2017, 77 million Nigerians or 40% of the population had no access to affordable, reliable and sustainable electricity. In practice, diesel- and petrol-fuelled back-up generators supply the vast majority of electricity in the country. In Nigeria's nationally-determined contribution (NDC) under the Paris Agreement, over 60% of the greenhouse gas emissions (GHG) reductions are foreseen in the power sector. The goal of this study is to identify and critically examine the pathways available to Nigeria to meet its 2030 electricity access, renewables and decarbonization goals in the power sector. Using published data and stakeholder interviews, we build three potential scenarios for electrification and growth in demand, generation and transmission capacity. The demand assumptions incorporate existing knowledge on pathways for electrification via grid extension, mini-grids and solar home systems (SHS). The supply assumptions are built upon an evaluation of the investment pipeline for generation and transmission capacity, and possible scale-up rates up to 2030. The results reveal that, in the most ambitious Green Transition scenario, Nigeria meets its electricity access goals, whereby those connected to the grid achieve a Tier 3 level of access, and those served by sustainable off-grid solutions (mini-grids and SHS) achieve Tier 2. Decarbonization pledges would be surpassed in all three scenarios but renewable energy goals would only be partly met. Fossil fuel-based back-up generation continues to play a substantial role in all scenarios. The implications and critical uncertainties of these findings are extensively discussed.

Key policy insights

- The 2030 electricity mix for Nigeria varies across the scenarios presented, with the most ambitious scenario achieving electricity access goals and partly meeting renewable energy goals.
- All three scenarios surpass the decarbonization targets of Nigeria's NDC for the power sector.
- The transformation of the power sector relies on a wide range of financial, policy and enabling environment-related conditions taking place in the near-term, some of which are in turn strongly influenced by larger political economy realities.
- Fossil fuel-based back-up generation plays a substantial role in all scenarios. Data availability for this technology remains a significant source of uncertainty.

ARTICLE HISTORY
Received 11 January 2019
Accepted 27 August 2019

KEYWORDS
Nigeria; SDG7; NDC; LEAP; energy access; electrification

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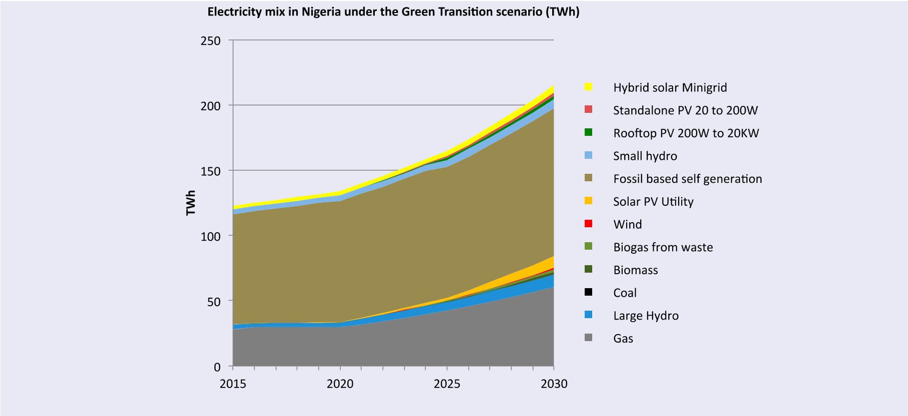
Supplemental data for this article can be accessed here https://doi.org/10.1080/14693062.2019.1661818.



1. Introduction

Nigeria has three key long-term ambitions for the electricity sector: a capacity expansion target, namely, 30 GW of installed on-grid capacity by 2030, of which 13.8 GW from grid-connected renewables (corresponding to 45% of total capacity and 30% of generation, respectively)[1]; the goal of universal electrification by 2040, and of 90% electrification by 2030; and the emission reduction targets in its nationally-determined contribution (NDC) under the Paris Agreement (FGN, 2015, 2016; FMPWH, 2016). Regarding the latter, Nigeria pledged a 20% unconditional reduction of its Business-as-Usual (BAU) greenhouse gas emissions (GHGs) by 2030, and a 45% reduction, conditional on financial, technical and capacity building support for implementation. Over 60% of these reductions are foreseen in the power sector.

There is a lack of scenario studies that look at the intersection of these three policy goals in Nigeria. Research in the area in general suffers from strong data inadequacies and limitations in gaining access to expert knowledge that is available but fragmented.

The goal of this study is to contribute to planning and decision-making by identifying and critically examining the possible pathways available to Nigeria to meet its electricity access, renewables and decarbonization goals in the power sector.

The following section presents the background on the challenges and opportunities in Nigeria's power sector and reviews key literature (Section 2). Section 3 presents the methodology including stakeholder validation, general scenarios, key assumptions and modelling approach. The following sections present the results (Section 4) and discussion (Section 5).

2. Background

Nigeria is a lower-middle income country, with annual per capita income of about US$2,500 (World Bank, 2018a). It is Africa's largest economy, and one in seven Africans is Nigerian. Despite Nigeria's significant human and natural resource capital, around a third of the 180 million Nigerians live below the national poverty line, with around another third just above (DFID, 2018). Nigeria is set to surpass the United States to become the world's third most populous country by 2050 (UNDESA, 2017).

According to official statistics, 77 million Nigerians have no access to grid power (IEA, 2018) and 80% of those with grid access use expensive diesel- and petrol-fuelled back-up generators as an alternative to the unreliable grid supply (IEA, 2017). Other surveys indicate that there could be as many as 120 million people, or 75% of the population, currently living without access to reliable and affordable power (de Boer, 2018).

Nigeria's insufficient generation and transmission capacity and the high costs of self-generation affect all aspects of the economy, from rural livelihoods to manufacturing and exports. Households and SMEs spend two to three times more on kerosene, diesel and petrol than they do on grid-based electricity (All On, 2016). In industry, government figures suggest that the cost of self-generating power makes Nigerian products about a third more expensive than imported products (FMITI, 2014).

Today's available on-grid peak generation averages 4 GW (NESISTATS, 2018) and the wheeling capacity of the grid is around 5.5 GW. Nigeria's on-grid generation is dominated by natural gas power stations (85% of available capacity) and three large hydropower plants (14%) (FGN, 2016). Currently, gas generation plants are severely constrained by availability of fuel. It is estimated that, with adequate gas supply, an average of 2 GW could be added to the country's daily peak generation (NESISTATS, 2018). In practice, diesel and petrol back-up generators supply the vast majority of power in the country. There is considerable uncertainty around the extent of fossil fuel-based self-generation but based on the number of generators imported annually it is estimated that there was around 15 GW of diesel and petrol-based generation installed capacity in the country in 2015 (FGN, 2016; Solar Plaza, 2017), with other estimates pointing at 16 GW just in the area of Lagos. Market segmentation data show a dominance of small and medium-scale generators in the 5–75 kVA range in terms of market volume (6WResearch, 2018).

The transformation of Nigeria's power sector faces various and interconnected challenges, some of which are common to both grid-based and decentralized electricity. The key challenges that they have in common are lack of finance, high investment risks and a poor enabling environment (World Bank, 2016b).

The grid-based sector suffers from: insufficient generation, transmission and distribution infrastructure (FGN, 2017), gas supply and water management bottlenecks (Occhiali & Falchetta, 2018), and corruption (Roy & Ibrahim, 2018; SERAP, 2017). In particular, the financial illiquidity of the market remains one of the most significant challenges for the sector (NERC, 2018a). This challenge is partly due to the lack of cost-reflective tariffs, high technical losses, and commercial losses of distribution companies under the prevailing practice of estimated billing. In addition, the potential of grid-based generation is constrained by a poor transmission and distribution grid. Its restoration and expansion are estimated to require an annual investment of US$1 billion for the next ten years (TCN PMU, 2017).

Recent policy developments geared towards tackling challenges in the grid-based electricity sector include new regulations on metering, rules allowing large consumers to buy electricity directly from generating companies (by-passing distribution companies), and feed-in tariffs for renewables (NERC, 2015, 2018b).

Different power generation technologies are at different levels of maturity in Nigeria, and there is a nascent market for renewables, both on- and off-grid. Fourteen solar PV companies signed power purchase agreements (PPAs) in 2016, with a combined capacity of 1 GW, though none have yet been commissioned.

Nigeria has a large potential off-grid market, be it through renewables-based mini-grids or through solar home systems (SHS) (All On, 2016; NESG & RMI, 2018). Standalone solar PV systems are already cost-competitive on a lifetime basis over diesel and gasoline generators (NESG & HBS, 2017). However, they have significant upfront costs and, without affordable financing, diesel generators are more accessible to households and small businesses. Hybrid (solar-battery-diesel) mini-grids have particularly high potential in Nigeria and thirty of them are currently in operation (RMI & REA, 2018). Some of the key barriers for investments in the off-grid electricity market are the lack of consumer affordability and financial viability of projects, the weak enabling environment, and the lack of data to make investment decisions. Recent policy developments geared towards tackling challenges in the off-grid-sector include regulations for mini-grids (NERC, 2018b), and a proposed bill for the removal of import tariffs on solar components. Moreover, a number of funds and financing partnerships have been launched to address key financing gaps in the deployment of mini-grids and SHS (GCF, 2018a; OGEF, 2018; World Bank, 2018b).

Despite its significant potential for savings, the role of energy efficiency in Nigeria is often overlooked and the market is in its infancy.

Nigeria's per capita GHG emissions are around 2 tCO_2e per capita (FGN, 2015), and the country represents around 1% of global GHG emissions. Nigeria, however, stands to suffer severely from climate change. The Climate Change Vulnerability Index consistently ranks Nigeria within the top ten most climate-vulnerable countries, and Lagos is the tenth most vulnerable city in the world (Verisk Maplecroft, 2013). The only comprehensive study on the economic costs of climate change in Nigeria points to losses in GDP of between 2–11% by 2020 if no adaptation measures are taken (ERM, 2009), a figure that is considered conservative judging by the economic losses caused by ongoing processes such as the shrinking of Lake Chad or crises such as the 2012 and 2018 floods. Costs associated with the 2012 floods alone amounted to around 2% of the annual GDP (FGN, 2013).

2.1. Modelling Nigeria's power sector transition

The last government-endorsed scenario study into Nigeria's energy future was carried out in 2014 by the Energy Commission of Nigeria (ECN, 2014). Since then, a number of other long-term scenario studies covering the Nigerian power sector, either partly or wholly, have been conducted (Cervigni, Rogers, & Henrion, 2013; FGN, 2015; Oxfam America, 2017; Oyewo, Aghahosseini, & Breyer, 2017; PwC, 2016). The most extensive one was carried out by the World Bank as part of a study on low-carbon development of the power, land use, agriculture, oil and gas sectors (Cervigni et al., 2013). It provided a 20-year outlook up to 2035, and identified the power sector as the key source for abatement of GHGs and consequent economic benefits of adopting low-carbon technologies. More recently, Oxfam and the University of California, Berkeley, modelled the Nigerian energy transition to reliable and affordable power by 2035 and explored the integration aspects of variable renewable resources (Oxfam America, 2017). Oyewo et al. (2017) modelled an energy transition from the current fossil fuel-based-system to a 100% renewable energy-based power system by 2050, where PV installed capacity reaches 400 GW by 2050 and battery storage dominates the balancing options. Finally, the modelling that supported the Nigerian NDC (FGN, 2015) pointed at efficiency of future gas power plants as holding the greatest potential for emission reductions, whereas the most cost-effective measure is the introduction of renewable energy into the mix, in particular in a decentralized manner.

In parallel to energy system models, a growing body of research uses geospatial data for electrification planning (Bertheau, Cader, & Blechinger, 2016; Mentis et al., 2015; Ohiare, 2015; World Bank, 2016a). Least-cost electrification studies address the economics of following different combinations of grid extension, mini-grids and standalone solutions to reach access goals. The literature for Nigeria indicates that, while grid extension is the least-cost solution in the long term, off-grid solutions have an essential role to play during the transition, bringing about important socio-economic benefits. Currently, no official strategy exists in Nigeria to harmonize grid extension plans with the deployment of off-grid solutions.

3. Method

3.1. Stakeholder validation

Consultation with representatives of stakeholder groups was central to the design of the scenarios presented in this paper. Stakeholders in the main segments of the power sector (policy, regulation, finance, technical assistance, private firms, advocacy) were involved through interviews in the development of the scenarios, validation of the underlying assumptions and assessment of their critical implications and uncertainties. A total of 28 expert interviews and small-group discussions were held. Key government institutions consulted included the Federal Ministry of Power, Works and Housing, the Energy Commission of Nigeria and the Rural Electrification Agency. Information on the investment pipeline was complemented by interviews with international development partners and private sector actors. The interviews resulted in valuable expertise on a range of issues, including underlying conditions and scenario storylines, demand forecasts, on-grid value chain, and off-grid market developments. It is worth noting that many experts found it difficult to estimate demand and supply figures beyond 2025. As a result, 2030 figures were often extrapolations of estimates they provided for 2020 and 2025, showing the difficulty of making long-range projections especially due to data constraints, political uncertainties, and a lack of long-term integrated planning for the sector.

Stakeholders were engaged via semi-structured interviews, and in some cases, small focus groups of experts focusing on a single issue such as, for example, mini-grids. The interviews were conducted between September 2018 and January 2019. Further information was obtained during several workshops of sectoral experts organized by third parties. The final results of the study were validated during a half-day meeting by government stakeholders, with a view to securing their inclusion in the 2020 NDC update. Overall, a balance was maintained in the number of interviews with government stakeholders (13) and those from the private and other sectors (15). Some stakeholders commented only on specific technologies.

Stakeholder validation and, more broadly, stakeholder participation and engagement, are increasingly used in scenario building with the aim of improving the effectiveness and transparency of public policy as well as the acceptance of, and engagement in, long-term strategies. In the realm of energy and climate change mitigation, stakeholder-based scenario building has emerged recently as a method for eliciting required data and for improving interpretations of model outputs, as well as for translating the results of the analysis into strategies (Mathy, Fink, & Bibas, 2015; Schmid & Knopf, 2012; Wiebe et al., 2018). From a theoretical point of view, collaboration between researchers and stakeholders is seen as a prerequisite for trans-disciplinary research that enables societal transitions (Brandt et al., 2013). There is a broad set of methods for stakeholder engagement and no consensus on what degree of stakeholder involvement constitutes real engagement and empowerment. Stakeholder-based approaches are not common in scenario studies for developing countries.

3.2. The scenarios

Taking into account the background realities sketched out above, and in consultation with stakeholders, we drafted three possible scenarios and developed accompanying assumptions. The scenarios depict futures in which Nigeria either meets or fails to meet its electricity access goals, with the aim of exploring the potential effects of near-term developments. The scenarios hinge on the key challenges and opportunities faced by different segments of the power sector: grid-based electricity, sustainable off-grid solutions, and fossil fuel-based back-up generation. The three scenarios can be summarized as:

- **BAU:** a pessimistic scenario where sector transformation is slow, national plans are weakly implemented and development continues along historical trends. A significant share of the population (46.7%) remains unelectrified and/or continues to rely on diesel and petrol generators in 2030. The underlying driver is the lack of significant mitigation of investment risks (via finance, policy and enabling environment) for both on-grid (generation, transmission, distribution) and sustainable off-grid investments (mini-grids and standalone systems).
- **Green Transition:** a best-case and relatively disruptive scenario where all current plans are fully implemented, leading to substantial transformation of the power sector. Both the on-grid and the sustainable off-grid sectors develop at a fast pace, and by 2030, 90% of the population has access to electricity. Those connected to the grid achieve a Tier 3 level of access (in line with the World Bank's Multi-Tier framework (MTF) for electricity access (Bhatia & Angelou, 2015)[2]), and those served by sustainable off-grid solutions achieve a Tier 2 level of access (including residential, productive and public services use). This scenario relies on investment risks in the on-grid and sustainable off-grid sector being strongly mitigated through finance, policy and enabling environment measures, and there being a strong drive from the government for renewables-based generation. The electricity mix diversifies away from fossil fuel-based back-up generators, though these continue to play an important role.
- **Moderate Change:** a scenario that sees incremental improvements, mainly on gas-based and centralized solutions, and where the scale-up of decentralized and renewable energy markets is delayed. The roll out of the grid and gas pipeline network proceeds at a slow pace. A relatively high share of the population (34.1%) does not have access to electricity by 2030. There is no strong drive for renewables-based on-grid projects but continued reductions in the cost of renewable energy technologies eventually bring about their presence in the mix.

Each scenario is underpinned by more detailed qualitative assumptions about near-term developments in finance, policy and enabling environment that would drive the scenario. Examples of such near-term developments are the resolution of the liquidity challenges facing the on-grid sector (via roll out of meters, or the review of electricity tariffs scheduled to take place in 2019–20), and the greater availability of finance for decentralized solutions. The underlying assumptions for each scenario are described in the Supplementary Material. It is important to note that the individual statements listed on this table do not lead to specific quantitative effects in the model. Rather, they underpin the storylines of each scenario and, taken individually or as a whole, facilitated the elicitation of expert views on the quantitative demand and supply assumption values that are explained in the following sections. Moreover, the scenarios as a whole, as well as the individual statements listed in the Supplementary Material, were to a large extent refined and improved on the basis of stakeholder interviews.

3.3. Demand assumptions

For each of the three scenarios, different quantitative assumptions were developed for potential pathways for electrification and growth in demand for electricity. We explicitly chose to avoid deriving demand assumptions from macroeconomic assumptions. The model underlying Nigeria's NDC (FGN, 2015) incorporated the government's projections of 5% annual GDP growth rate. The NDC (initially presented as Nigeria's Intended NDC in the run-up to the 2015 Paris Climate Conference) was prepared before the 2016–7 economic recession, during which the Nigerian economy contracted by 1.6%, after having grown at an average of 5.7% over the previous decade (2005–2015) (World Bank, 2018a). Slow economic recovery is forecast in the coming years, with the IMF reporting a GDP growth of 0.8% in 2017 and projecting a 2% growth in 2018 and coming years (IMF, 2018). The NDC's demand scenarios assume that Nigeria would reach a per capita electricity consumption of around 2,000kWh by 2030 (including industrial demand), in line with similar lower-middle income countries (Cervigni et al., 2013). This equates approximately to Tier 5 of the World Bank's MTF for electricity access (Bhatia & Angelou, 2015) in 2030. The scenario contained in Nigeria's Sustainable Energy for All (SEforALL) Action Agenda, in turn, projects an annual consumption per capita of 1,126 kWh by 2030 (FGN, 2016; FMPWH, 2016).

Based on stakeholder consultations, this study took a more conservative view on what level of access could be achieved by 2030. It is important to note that this assumption is not broken down into demand sectors (i.e. buildings, industry, agriculture) and is not split into urban vs. rural segments of the population. Moreover, for simplicity, energy efficiency improvements are not taken into account (both the SEforALL Action Agenda and the NDC assume efficiency improvements of between 0 and 2% per year). In our study, the main drivers for demand are:

- Population growth, assumed at around 2.5% per year, in line with UN projections (UNDESA, 2018).
- Electrification pathways, based on least-cost electrification plans carried out for five states in Nigeria (Blechinger, Cader, & Bertheau, 2019; NESP, 2017) and refined via stakeholder consultations. Based on existing electrification rates, population density, distance from the grid and other indicators, these studies modelled the optimal pace at which grid extension and densification investments should proceed, as well as the areas where mini-grids and SHS were viable over the transition period.
- A purpose-built definition of Nigeria's 2030 access goal in terms of the World Bank's MTF (Bhatia & Angelou, 2015), whereby those connected to the grid achieve a Tier 3 level of access, and those served by sustainable off-grid solutions (mini-grids and SHS) achieve a Tier 2 level of access, including residential, productive and public services use (Table 1). It is important to note that such a definition does not yet exist in Nigeria's national electricity access goals, and that it has been proposed as a framework assumption in this study on the basis of stakeholder consultations and model iterations. Official goals refer only to the proportion of the population that would have access to electricity. The electrification pathways for each scenario are depicted in Figure 1.
- An estimate of what demand there will continue to be for fossil fuel-based back-up generation in each of the scenarios (Table 2).

The resulting electricity demand assumptions for each scenario are depicted in Figure 2.

3.4. Generation and transmission capacity assumptions

The assumptions for the development of generation capacity are shown in Tables 3 and 4, whereas those for transmission and distribution are shown in Table 5. In correspondence with the general storylines for the

Table 1. Assumptions for level of access achieved.

	2015	2020	2025	2030
Off-grid (kWh/year/person with sustainable off-grid access)	0	20	50	100
On-grid (kWh/year/person with grid access)	243.4	250	350	500

Note: Base year values derived from FGN (2016). Note that the yearly per capita values include residential, productive and public services use.

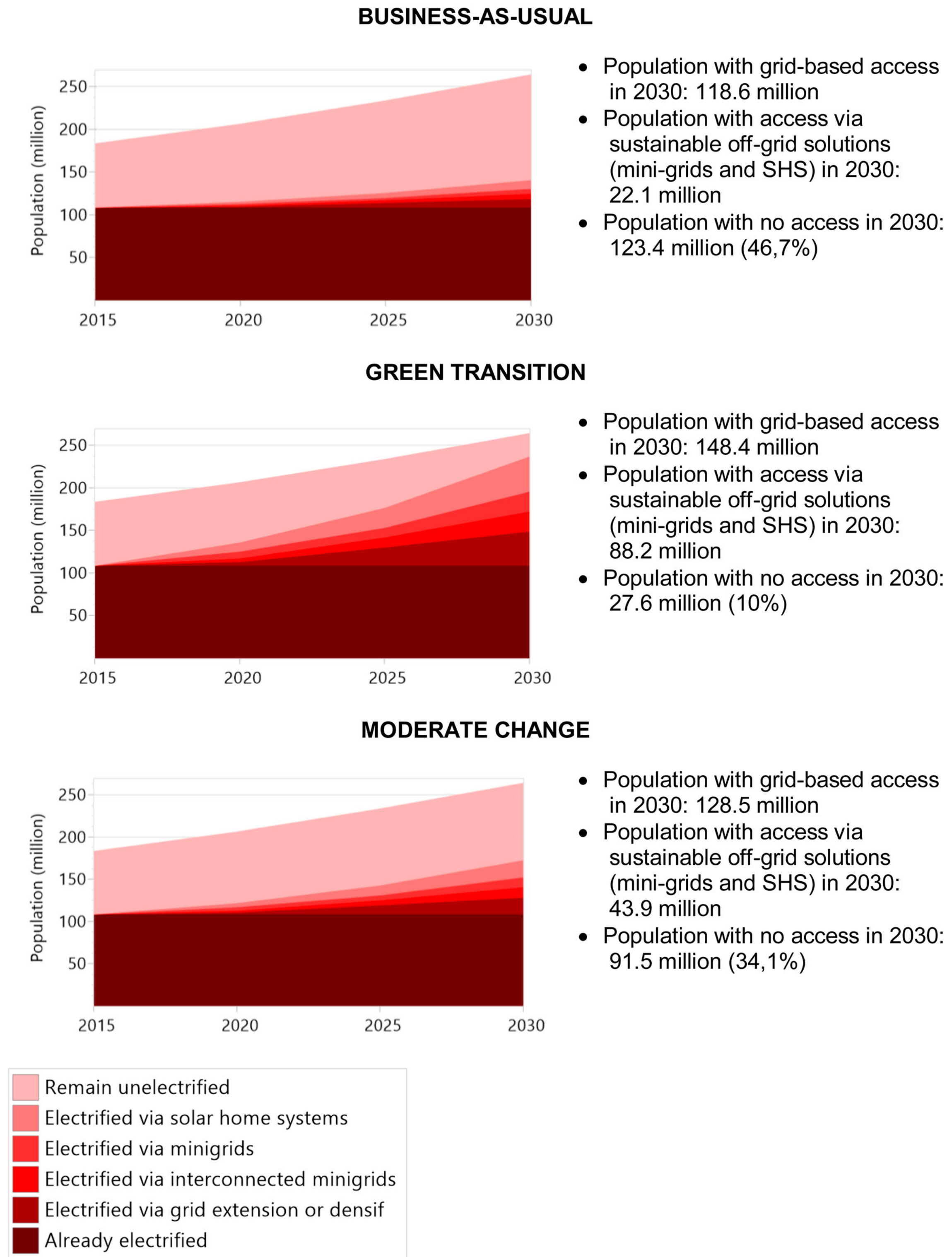
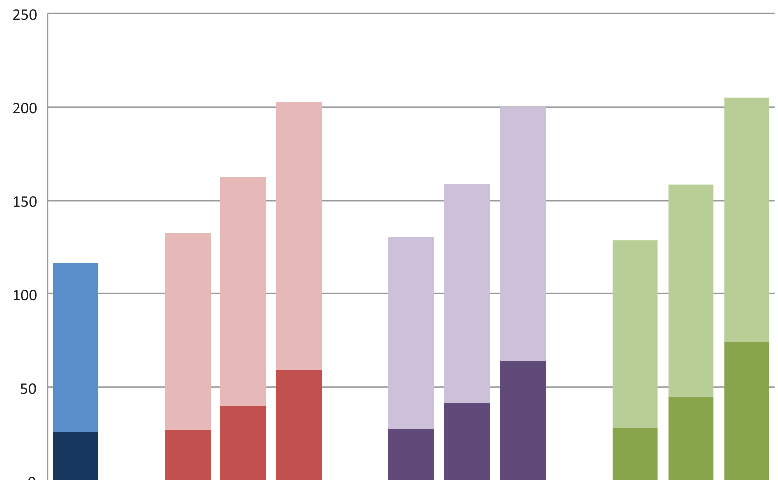


Figure 1. Electricity-access pathways for each scenario. Sources: NESP (2017) and stakeholder consultations. The pathways form the basis for the demand assumptions that were inputted into the model.

Table 2. Assumptions for growth in demand for fossil fuel-based back-up generation for each scenario.

Demand for fossil-based back-up generation (TWh)	2015	2020	2025	2030
BAU – 3% annual growth rate	90.6	105.0	121.8	141.2
Green Transition – 2% annual growth rate	90.6	100.0	110.4	121.9
Moderate Change – 2.5% annual growth rate	90.6	102.5	116.0	131.2

Note: Base year values derived from FGN (2016). Projected growth rates based on stakeholder consultations and (6WResearch, 2018).



	Baseline	BAU 2020	BAU 2025	BAU 2030	MOD 2020	MOD 2025	MOD 2030	GREEN 2020	GREEN 2025	GREEN 2030
Off-grid demand (TWh)	90.6	105.1	122.3	143.4	102.7	117.1	135.6	100.5	112.8	130.8
On-grid demand (TWh)	26	27.4	39.9	59.3	27.7	41.7	64.3	28.2	45.4	74.2

Figure 2. Electricity demand assumptions for each scenario, based on electricity access pathways and assumptions on development of fossil fuel-based back-up generation. Sources: baseline values derived from FGN) (2016).

Note: Off-grid demand includes both fossil fuel-based back-up generation and sustainable solutions (mini-grids and SHS).

Table 3. On-grid generation capacity assumptions for each scenario.

	Scenarios									
		BAU			GREEN			MODERATE		
On-grid Generation Capacity (GW)	Base year 2015	2020	2025	2030	2020	2025	2030	2020	2025	2030
Gas	5.845	5.845	6.500	7.500	6.200	7.500	10.000	6.000	7.000	8.500
Large Hydro	1.383	1.383	1.890	1.890	1.890	3.000	4.000	1.600	2.000	2.500
Coal	–	–	0.400	0.400	–	–	–	–	0.400	0.400
Biomass	–	–	–	0.050	0.020	0.100	0.500	–	0.020	0.100
Biogas from Waste	–	–	–	0.050	0.020	0.100	0.500	–	0.020	0.100
Wind	–	–	0.010	0.100	0.010	0.200	0.500	–	0.050	0.150
Solar PV Utility	–	0.070	0.200	0.500	0.120	1.080	5.000	0.120	0.500	1.000

Note: Base year and projections based on public sources (Future Energy Nigeria, 2017; Office of the VP & Power Africa, 2015) that were then refined via stakeholder consultations.

scenarios, in the Green Transition scenario, both on- and off-grid technologies scale up at what sector experts consider to be the fastest possible pace. This means, for example, that natural gas installed generation capacity increases to 6.2 GW by 2020, mainly due to refurbishment of existing plants, and that 10% of the approximately 13 GW pipeline of natural gas projects currently planned or under construction in Nigeria is actually realized by 2025. A further 2.5 GW comes online during the following five-year period (2025–2030), meaning a doubling of the capacity installed over the previous five years. The rates of implementation are considerably lower in the

Table 4. Off-grid generation capacity assumptions for each scenario, including both fossil fuel-based self-generation and sustainable off-grid solutions.

Off-grid Available Generation Capacity (MW)	Base year 2015	Scenarios: BAU 2020	BAU 2025	BAU 2030	GREEN 2020	GREEN 2025	GREEN 2030	MODERATE 2020	MODERATE 2025	MODERATE 2030
Fossil-fuel based Self-Generation	25,000	28,981	33,597	38,949	27,602	30,474	33,646	28,285	32,002	36,207
Small Hydro	45.0	46.0	50.0	53.0	50.0	65.0	80.0	46.0	53.0	60.0
Rooftop PV (Residential, C&I, Public – 200W to 20 kW)	10.0	20.0	40.0	80.0	20.0	70.0	170.0	20.0	70.0	170.0
Standalone PV (20W to 200W)	1.0	4.5	7.0	10.0	7.0	20.0	35.0	6.0	10.0	20.0
Hybrid Solar Mini-Grid	–	1.2	3.6	7.2	2.0	20.0	100.0	2.0	5.0	10.0

Note: Base year and projections based on public sources (6WResearch, 2018; GOGLA et al., 2019; HBS & CSJ, 2017; UNIDO, 2016) that were then refined via stakeholder consultations.

Table 5. Transmission and distribution capacity assumptions for each scenario.

Transmission and Distribution capacity (GW)	2015	2020	2025	2030
BAU	5.5	6.0	7.0	8.0
Green Transition	5.5	7.5	10.0	15.0
Moderate Change	5.5	6.0	8.0	10.0

Note: Base year and projections based on stakeholder consultations.

BAU and Moderate scenarios. All scenarios assume, based on the evaluation of the investment pipeline, that the gas power plant fleet continues to be dominated by single-cycle turbines. We note the NDC assumes an increase in investment in combined cycle technology.

Large hydropower sees around a third of the 6GW pipeline realized by 2025, whereas in the BAU scenario only 500 MW are added. For grid-connected solar PV, the Green Transition scenario assumes that two of the fourteen PPAs that were signed in 2017 reach financial close by 2019 (CSEA Africa, 2019; Nextier Power, 2018), bringing the installed capacity to 120 MW in 2020, then increasing to 1.1 GW in 2025 and 5 GW in 2030.

The on-grid investment pipelines (projects planned or being commissioned) were estimated from publicly available sources (Future Energy Nigeria, 2017; Office of the VP & Power Africa, 2015) and refined via stakeholder interviews. For off-grid generation, data scarcity meant that most baselines and scale-up projections were developed on the basis of stakeholder interviews only. For example, the status of functioning mini-grid projects by 2015 and the possible scale-up rates were estimated during interviews with private mini-grid developers and development organizations active in the energy access space.

In the Green Transition scenario there is a disruptive scale-up of off-grid renewables-based solutions: over 1 million solar standalone systems are installed by 2023. This is in line with the goals of the Nigeria Electrification Project (World Bank, 2018b) and was checked against the latest market trend data (GOGLA et al., 2019). For mini-grids, we assumed that there would be a gradual implementation of the various funds currently being pledged over the next 10 years, which would result in around 100 MW of mini-grid projects being successfully implemented by 2030. The baseline values and projections for small hydro, commercial and industrial PV, and fossil fuel-based self-generation (i.e. diesel and petrol generators) were based on existing studies (6WResearch, 2018; HBS & CSJ, 2017; UNIDO, 2016) but extensively refined as a result of stakeholder consultations. There remain high levels of uncertainty in the assumptions for these technologies.

The assumptions for transmission and distribution (Table 5) were developed through stakeholder consultations. The government's grid expansion goals are significantly higher than our assumptions (e.g. 10 GW of wheeling capacity are targeted by 2020), but the sector is inadequately funded (TCN, 2018; TCN PMU, 2017). There is currently no official strategy to harmonize grid expansion plans with the roll-out of off-grid solutions.

As well as capacity assumptions, other technical variables such as process efficiency, capacity credit and capacity factors were derived from previous studies (FGN, 2015; NESG & HBS, 2017) and are available on the full data set that is made available with the paper (LEAP, 2019). The sources used in those studies are Nigerian public documents (e.g. Cervigni et al., 2013; NERC, 2012, 2015; Oladokun & Asemota, 2015), complemented with international sources where necessary.

3.5. Model

We simulate the resulting electricity supply mix and emissions of the three scenarios with the help of the LEAP (Long-range Energy Alternatives Planning) tool (Heaps, 2016). LEAP, a medium- to long-term modelling tool for energy policy analysis and climate change mitigation assessment, was also used to inform Nigeria's NDC, as well as the NDCs of 34 countries, especially in the developing world (GIZ, 2017).

Our study uses LEAP as an energy accounting tool, which is one of several modelling methodologies it can support.[3] First, we used LEAP to develop a model of Nigeria's on- and off-grid electricity systems. The tool allows for flexibility in the structure and hierarchy of final demand and energy supply modules. This proves important in the Nigerian context, where severe data shortages exist, and where electricity supply technologies that are not subject to transmission losses (i.e. off-grid technologies) play an important role in the system.

The model's key exogenous assumptions are the final electricity demand, the maximum installed capacity of different generation technologies and the transmission capacity of the grid (Figure 3). With these, and using its rules-based algorithms, LEAP determines endogenously the future capacity additions and electricity production that will meet demand under each of our scenarios, and estimates the resulting GHG emissions.

4. Results

The results indicate that in 2030, Nigeria's electricity mix continues to be dominated by fossil fuel-based self-generation (between 53 and 62% of the mix, depending on the scenario) and natural gas generation (26–29%) (Figure 4). The Green Transition scenario achieves a total output of 215,03 TWh, which in per capita terms

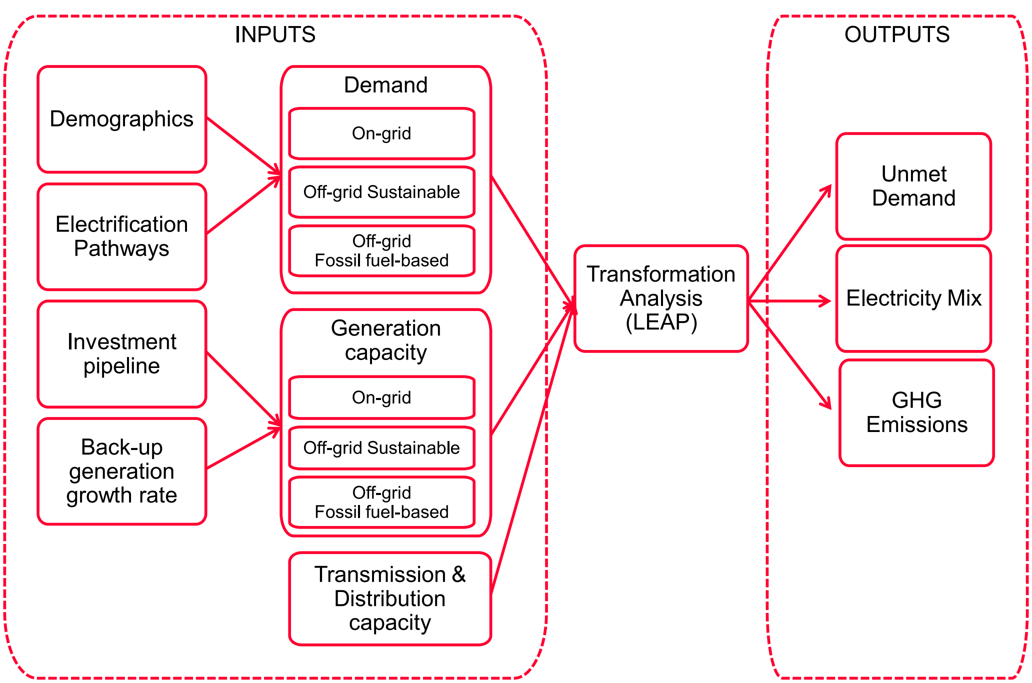


Figure 3. Schematic view of model assumptions (inputs) and results (outputs). Expert stakeholder views informed the inputs.

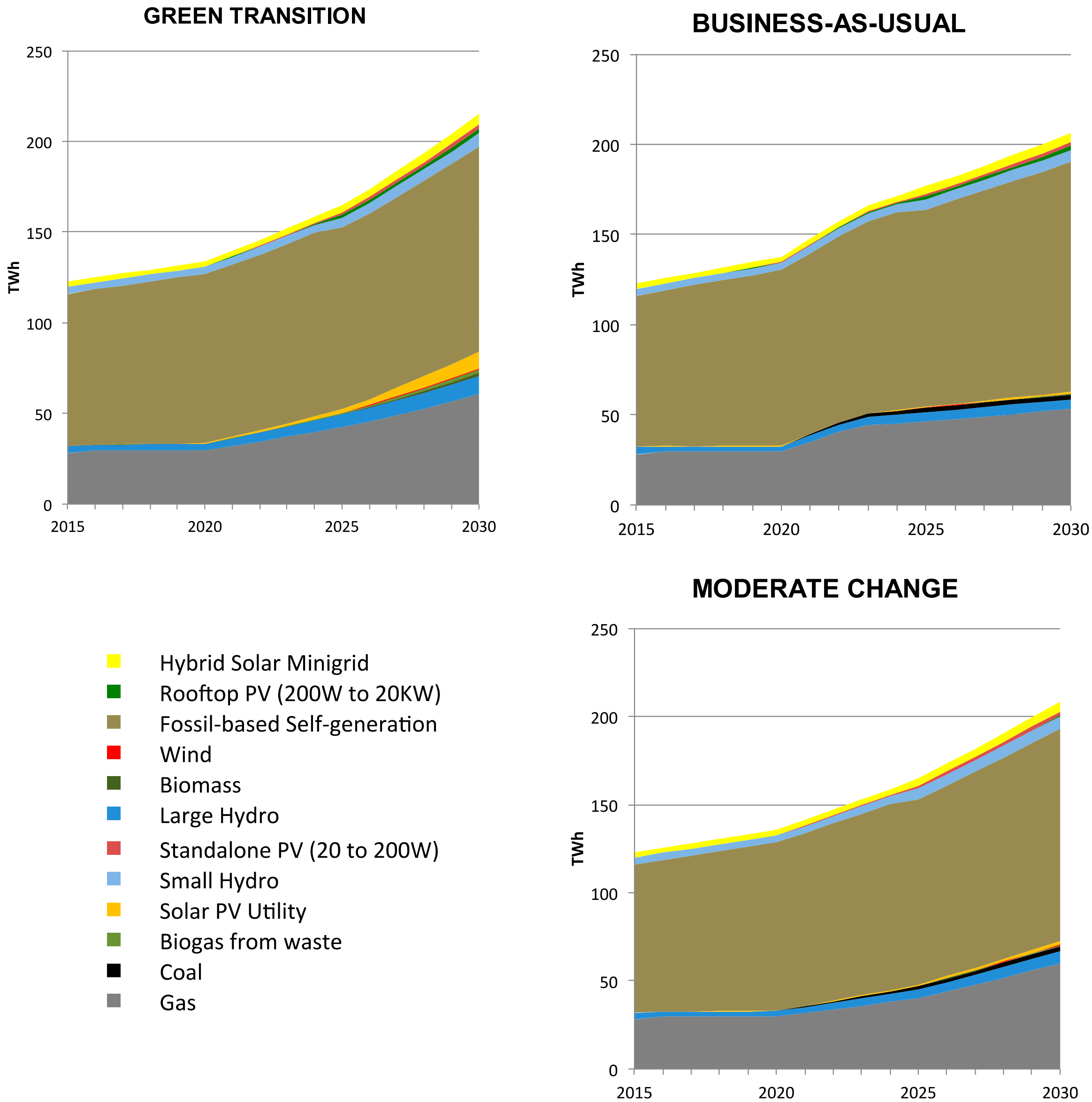


Figure 4. Electricity mix for each scenario (TWh).

equates to 814 kWh per person per year, or 386 kWh per year if the fossil fuel-based generators are excluded. This is significantly below the yearly demand projected by Nigeria's NDC and SEforALL Action Agendas of around 2,000 kWh and 1,000 kWh per capita by 2030, respectively.

4.1. Access goals

On the basis of our assumptions on supply (generation, transmission and distribution capacity), the demand in the Green Transition scenario is met. In other words, the Green Transition scenario meets the '90% electricity access by 2030' goal as defined in this study. Specifically, this means that 148.5 million people would be connected to the grid by 2030 and would have a Tier 3 level of energy access (500 kWh per capita per year) and that those with sustainable off-grid access would shift from zero to Tier 2 (100 kWh per capita per year).

The BAU and Moderate scenarios are also able to meet demand, which in these cases was much lower given the lower assumed electrification rates (53.3% and 65.9%, respectively).

It is important to recall that the electrification pathway underlying the Green Transition scenario sees 88.2 million people receiving electricity from sustainable off-grid solutions by 2030, including over 40 million from standalone systems. While this was considered feasible by some of the experts consulted, it would entail an unprecedented speed and scale of transition in the off-grid sector. Moreover, the scenarios remain rather reliant on the assumptions on the scale-up of mini-hydropower, with almost half of the demand for sustainable off-grid electricity being met with these solutions.

4.2. Renewable energy goals

The Green Transition scenario would result in a 14.7% share of renewables in the energy mix by 2030, when excluding large hydropower. This is in line with the government's goal of 15%. However, when large hydropower is included, the share of renewables in the mix is only 19.3%, far from the 30% government goal. In other words, the renewable energy targets are only partly met. Nonetheless, this substantial share would contribute greatly to accelerating the transition towards meeting longer term goals beyond 2030. The BAU and Moderate scenarios result in a share of approximately 9% for renewables in the mix excluding large hydro, and 12% when including large hydro.

4.3. Emissions goals

Nigeria's NDC does not have a specific emissions goal for the power sector, but its most ambitious, i.e. 'conditional', scenario sees power sector emissions roughly doubling from 164.5 $MtCO_2e$ in 2015 to around 300 $MtCO_2e$ by 2030. The emissions of all three scenarios in our study are significantly lower than that level, ranging from 146 to 153 $MtCO_2e$ in 2030 (Figure 5). In other words, according to our assumptions, the NDC's pledges for the power sector would be comfortably met in all three scenarios. It is important to note that this study used the same modelling tool and a similar model structure as the NDC, considered the same GHGs (CO_2, methane and nitrous oxide) and used the same Tier 1 emission factors for electricity generation.

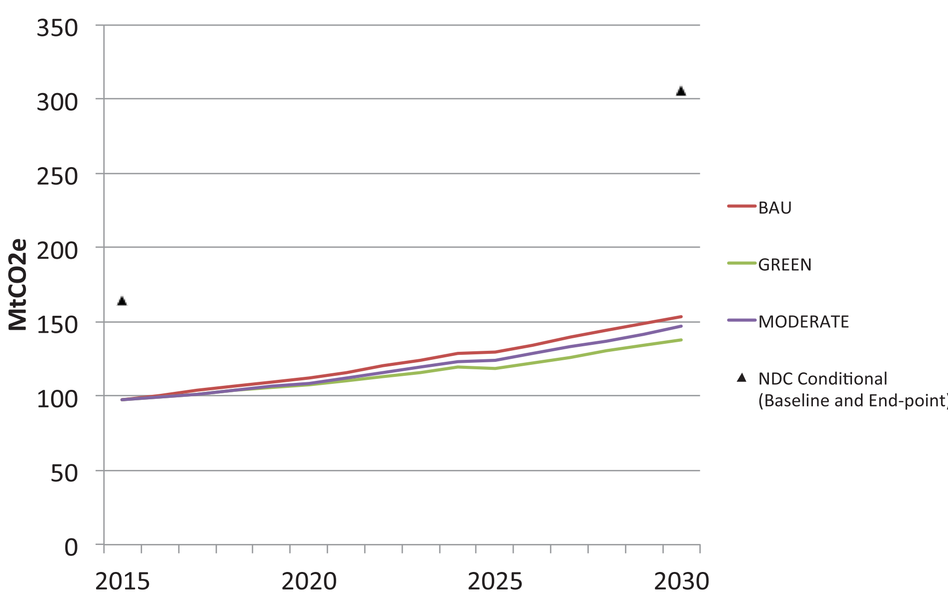


Figure 5. Emission pathways for all scenarios ($MtCO_2e$). Emission factors based on IPCC guidelines (2006)

The difference between the NDC emission pathways and this study's is due to the underlying demand and supply assumptions. Specifically, we can distinguish the following drivers for the differences:

- 2015 baselines: the NDC assumed significantly higher installed capacity for gas stations. In our study we used only operational (rather than nameplate) plant capacity and refined the values through expert interviews.
- Emission pathways: demand assumptions were the main reason for the difference. The NDC assumed a 5% rate of growth in GDP per annum, whereas our study avoided macro-economic drivers of demand and built demand on the basis of feasible electrification rates, as revealed by least-cost electrification studies. Supply assumptions also played a (smaller) role in the difference between the emission pathways.

The differences in emissions between the Green Transition, Moderate and BAU scenarios are mostly driven by the different role of fossil fuel-based back-up generators in each scenario. Incorporating other gases would likely make these differences larger, particularly in the case of diesel generators, which are important sources of black carbon and other short-lived climate pollutants (SLCP). A study into Nigeria's SLCP emissions and their health and economic costs is currently underway (CCAC, 2018).

5. Discussion

One of Nigeria's most demanding challenges today is to deliver electricity access to millions. Despite the recent privatization of generation and distribution, the establishment of a grid management company, and the adoption of accompanying legislation, Nigeria is considered to have one of the least developed policy environments to support energy access (World Bank, 2016b). Moreover, Nigeria's power sector has recently faced a national economic recession. This study aimed to explore the feasibility of a power generation mix that would meet electricity access, renewables and emissions reduction goals by 2030. We determined that under certain assumptions the targets can be achieved through a combination of on- and off-grid solutions.

5.1. Off-grid sector

On the off-grid side, a fast but plausible growth of the market for standalone PV and hybrid mini-grids could deliver a Tier 2 level of access (approximately 100 kWh per capita per year) to over 88 million people by 2030. Key underlying conditions for this would include: rapidly shifting financial flows from grid-connected investments to off-grid systems (SEforALL, 2018), coordinating grid expansion plans with roll-out of off-grid solutions (World Bank, 2016b), and improving capacity and standards. The BAU and Moderate scenario also see some growth, driven by the reduction in costs. However, they fall short of delivering on the access goals as defined in this study.

Stakeholders consistently highlighted the role that emerging financing tools and funds can play in triggering this rapid transition. Several development finance institutions have recently set up funds that underwrite or de-risk off-grid investments in Nigeria, provide guarantees to mini-grid and SHS system developers and financiers, or take a direct stake in investments. Commercial banks have also been targeted through finance programmes, with the Central Bank of Nigeria and the African Development Bank (AfDB) now supporting a commercial bank in the provision of preferential loan terms to renewable energy developers (Anyaogu, 2018). The French Development Agency (AFD) has also partnered with two Nigerian commercial banks to set up a credit facility for investments into renewables (SUNREF, 2018). The AfDB is also an investor in the Off-Grid Energy Access Fund (OGEF, 2018). The Green Climate Fund is supporting additional blended finance investments into Nigeria, by consortia led by AFD and FMO, the Dutch development bank (GCF, 2018b). The portfolio of the domestic sovereign green bond launched in 2017 includes NDC-compliant renewable energy projects (DMO, 2017).

Expert interviews revealed that there are currently about 100,000 PV standalone systems deployed in Nigeria (excluding solar lanterns and products below 20Wp) and around 30 operating hybrid solar-diesel mini-grids. This is a very small fraction of the very large market potential (GOGLA et al., 2019; NESG & RMI, 2018). A considerable number of international and national investors are currently active in the Nigerian market, but even for them, predicting the pace of market scale-up is very challenging, in particular for small-scale solar systems. Stakeholders have a wide range of views as to the speed with which off-grid can be scaled up, and the impact the investments will have on electrification pathways. In view of the limited experience in the scaling up of off-grid operations in the country and an evident lack of capacity among project developers, concern has been expressed that a sudden large inflow of investment, into what is arguably an immature market, may lead to sub-standard projects.

Our quantitative scenarios do not fully capture the interaction between the off-grid and on-grid sectors, and how the development of one sector might influence the other. For example, there is high uncertainty around how a strengthened grid supply and availability of sustainable off-grid solutions would affect the rate of replacement of diesel and petrol back-up generators (Farquharson, Jaramillo, & Samaras, 2018). Another example is inter-connected mini-grids, which were seen by stakeholders to play a crucial role in certain segments of the market during the transition. Mini-grids may actually develop much faster in rural and peri-urban areas that are already grid-connected but are loss-making for the on-grid distribution companies (Graber, 2018).

The Green Transition scenario sees a relative deceleration in the growth of the petrol and diesel back-up generator market, due to the emergence of sustainable access solutions. However, there would still be a very large share of fossil fuel-based back-up generation in the mix (53% of the total output in 2030, compared with 58% and 62% in the Moderate and BAU scenarios, respectively). In the absence of sufficiently large sustainable off-grid markets, or of clear policy signals (e.g. fuel price reform, import duties) – which are unlikely to be put in place in the near-term – the high willingness to pay for power will continue to drive this part of the electricity mix and many millions of households and businesses will still depend on diesel and petrol back-up generators.

A number of studies point towards the significant health impacts and costs to the economy of petrol and diesel generators in Nigeria (Awofeso, 2011; Climatters, 2018; Oguntoke & Adeyemi, 2017). Exposure to fine particulate matter accounted for 22% of infant deaths in Sub-Saharan Africa (Heft-Neal, Burney, Bendavid, & Burke, 2018). The contribution of emissions from diesel generators to this has not been established (Farquharson et al., 2018), but reducing reliance on back-up generation is likely to accelerate the achievement of health-related sustainable development goals (SDGs) in Nigeria (especially SDG-3).

This study purposely omitted energy efficiency improvements from the demand assumptions, with the aim of reducing complexity and therefore engaging more effectively with stakeholders who are unfamiliar with energy modelling and scenario building. However, it is widely acknowledged that energy efficiency is set to be a catalyst for off-grid electrification (GOGLA et al., 2019). The growth of markets for energy-efficient appliances such as televisions and fans in Nigeria will be an important factor in the successful realization of the off-grid electrification pathway in the Green Transition scenarios. Future studies should address the role of efficiency in off-grid electricity demand.

5.2. On-grid sector

Based on the assumed rates of growth in gas-based generation, coupled with significant improvements in the grid, a moderate increase of large hydropower and introduction of non-hydro renewables-based generation, particularly solar PV, the current level of access could increase significantly. However, this does not mean that the electricity mix changes dramatically from the current relative shares. The Green Transition scenario sees 28% of the 2030 output coming from natural gas, 5% from large hydropower and 4% from utility scale solar. In the case of gas or hydro, this only slightly surpasses the 2015 shares (23% and 3%). It is important to remember that this scenario relies on there being wide-ranging improvements in financial, policy and enabling environment-related conditions in the near-term, including the restructuring of distribution companies that are currently not creditworthy. A very important assumption in the Green Transition scenario is that the regulated electricity tariffs are reviewed as scheduled in 2019–20.

It is important to note that this study does not take into account potential gas supply bottlenecks. Nigeria's plan to unlock its domestic gas market is hindered by high cost of finance for gas transport infrastructure as well competition with the export market (Occhiali & Falchetta, 2018). Similarly, the potential expansion of hydropower in Nigeria must be understood in the context of a poor track record of project completion. Many of the large hydropower projects in Nigeria have faced significant overruns and increases over the planned costs.

The non-hydro renewable energy resource that is currently of most interest in Nigeria is solar PV. At present, there is no significant utility scale PV generation, but it is of high priority for the government due to its potential to stabilize the grid in the North of the country and reduce transmission losses. Predicting what will be the share of biogas, biomass and wind-based electricity in the mix by 2030 is highly challenging. Both Nigerian and international data show good prospects for biomass-based generation. However, the market is particularly immature and there is a significant lack of knowledge regarding the most promising feedstock and conversion technologies, and the effects of competition with agricultural land use.

Although our study did not explicitly consider energy efficiency, in reality, there are likely to be efficiency gains even if no measures are taken, due to the reduction in costs of energy efficiency innovations. There is moreover a large efficiency potential to exploit in all demand sectors (GIZ NESP, 2015), which is likely to bring about significant savings and productivity gains. Suitable policies and standards (e.g. building code, Minimum Energy Performance Standards for lighting and air conditioners, ISO 50001) and a number of capacity-building initiatives are in place in Nigeria, but there are also large gaps in enforcement and monitoring, and an almost total lack of financing. The National Energy Efficiency Action Plan (NEEAP) sets several ambitious targets for 2030, such as increasing the share of new energy efficient buildings by 30% and almost 100% efficient lighting in housing by 2030.

5.3. Methodological implications

The design of the qualitative scenarios in this study relied on a deep understanding of the realities of the sector based on numerous stakeholder interviews. This approach is, however, not without its limitations. The set of underlying conditions (financial, policy and enabling environment-related) that underpin the scenarios are very dynamic and uncertain, and were a source of much debate during stakeholder discussions. Moreover, their effect is strongly influenced by larger political economy realities and they are themselves strongly interconnected.

The two exogenously defined drivers of this scenarios – demand and capacity installed – were also co-created with the support of experts and validated by numerous stakeholders of the power sector (policy, regulation, finance, technical assistance, private firms, advocacy). Finally, the preliminary outputs from the simulation were fed into some of the stakeholder interviews.

This study sheds light into the use of LEAP as a tool in the emerging field of energy transition analysis in developing countries, and has striven to address some of the gaps in the application of energy planning models in developing economies (Debnath & Mourshed, 2018). One advantage of the tool is that it is flexible enough to use in environments with severe data shortages. Moreover its transparency and accessible interface suits stakeholder engagement processes. LEAP has been used before in Nigeria (e.g. Emodi, 2016; Ibrahim & Kirkil, 2018).

Nigerian on-grid power generators have not met natural customer demand since the 1990s, hence historic statistics are insufficient to understand the level of suppressed demand. To compensate for this, the scenarios used the standard Tier system and proposed that different segments of the population realize a different share of the suppressed demand by 2030. In terms of kWh, rural and low income segments would realize relatively less than those connected to the grid, but probably with comparatively greater socio-economic impacts. The approach allows us to introduce a measure of inclusivity into the scenarios (Practical Action, 2018).

Climate change impacts are not considered directly in the study, but influenced the assumptions on installed capacity for large hydropower. There is scarce information on the vulnerability of hydropower to climate change in Nigeria. Given Nigeria's high vulnerability to climate change, water needed in both thermal and hydroelectric generation could become a limiting factor in the future.

Paucity of data remains a critical barrier to meaningful planning. In particular, some of the key areas of uncertainty include the 2015 baseline for fossil fuel-based back-up generators, as well as their pace of scale-up and the relationship between scale-up of sustainable off-grid access solutions and the shift away from back-up generators. The figures on techno-economic potential for small hydropower in Nigeria also warrant further investigation.

There is great convergence across SDGs when it comes to access to energy and mitigation of climate change (Antwi-Agyei, Dougill, Agyekum, & Stringer, 2018; McCollum et al., 2018; Nerini et al., 2019). The implementation of the pledges contained in developing country NDCs will be driven largely by the synergies between low-carbon transitions and the SDGs. Next steps stemming from this study could therefore include an assessment of the scenarios in terms of their impacts on goals other than SDG7 (Affordable and Clean Energy) and 13 (Climate Action), such as poverty alleviation, food security, job creation, gender, social inclusion and air quality (Markkanen & Anger-Kraavi, 2019; Nerini et al., 2018; Power for All, 2019; Verolme, 2017). Future research could moreover focus on testing the sensitivities of the results to the most critical demand and supply assumptions.

The present study does not invoke LEAP's cost modelling capabilities. Including cost assumptions into the LEAP tool or complementing the use of LEAP with other geo-spatial analysis tools would provide further insights into the potential of different technologies (Moksnes, Korkovelos, Mentis, & Howells, 2017).

Deepening the detail of NDC emissions scenarios is of great importance to accelerate their implementation. Our research also has the potential to make a significant contribution to the enhancement of Nigeria's NDC, in a context where the current set of NDCs have been deemed inadequate for meeting the 'well-below 2°C' goal of the Paris Agreement (Rogelj et al., 2016). Moreover, our study contributes to the emerging field of energy transition analysis and stakeholder-based scenario-building in developing countries (Osunmuyiwa, Biermann, & Kalfagianni, 2018; Palazzo et al., 2017; Waisman et al., 2019).

6. Conclusion

Drawing on published data and stakeholder interviews, we identified pathways along which Nigeria's power sector might transition up to 2030. The results reveal that, in the most ambitious Green Transition scenario, Nigeria could meet its electricity access goals and decarbonization pledges, and partly meet its renewable energy goals.

In contrast, the BAU and Moderate scenarios point towards a delay in the transition of the power sector, where population growth overshadows the impact of policies and investments, and access to electricity stagnates or decreases by 2030. It is worth noting that all three scenarios in this study surpass the decarbonization targets of Nigeria's NDC. Moreover, fossil fuel-based back-up generation (chiefly small-scale diesel and petrol-fuelled generators) plays a substantial role in all three scenarios. Data availability remains a significant source of uncertainty for this generation technology and warrants specific research.

A better understanding of the links between electrification strategies, capacity expansion and mitigation pathways, as described here, can support the planning process and make a significant contribution to the updating of Nigeria's SEforALL Action Agenda and its NDC. This improved understanding can also, to some extent, support policy and investment decisions.

Notes

1. Goals for grid-connected renewables include medium and large hydropower. When excluding them, the targets are 9.1GW of installed capacity by 2030, generating around 25 TWh/year. This corresponds to 30% of total capacity and 15% of total generation. Other targets include the proportion of the rural population that are served with off-grid renewables (25% by 2020 and 40% by 2030).
2. The Multi-tier Framework (MTF) was designed in 2015 under the SEforALL initiative, and provided a new definition and metric of energy access that is broader than binary metrics (electricity connection vs. no connection), and takes into account the quantity and quality of energy being accessed. The framework has proven to be a useful tool for measurement, goal-setting, investment prioritization, and tracking progress. The MTF follows a multidimensional approach. For example, where it concerns electricity supply, the following attributes are taken into account: capacity, duration, reliability, quality, affordability, legality, and health and safety. Our study built its demand assumptions with the goal of providing some degree of comparability with the MTF, so as to be of greater relevance in the light of upcoming MTF-based measurements and targets in Nigeria. To this end, some attributes of the MTF, chiefly the yearly consumption and supply levels, were used as criteria for defining tiers of access in our scenarios. Some important differences between the MTF's approach and our study's are: we summed annual household electricity consumption levels (as defined Table ES.3 of Bhatia and Angelou (2015)), productive use supply levels (Table ES.6) and public community infrastructure levels (Table ES.8). Moreover, for ease of comparison with available Nigerian statistics, we converted the metric from a 'per household' to a 'per capita' metrics. The result is an approximate yearly per capita values for Tier 2 (100 kWh) and Tier 3 (500 kWh). It is important to remember that Nigeria's current national electricity access goals do not follow this approach and refer only to the proportion of the population that has access to some source of electricity.

3. LEAP is a scenario-based modelling tool that supports a wide range of different modelling methodologies, from bottom-up accounting techniques to top-down macroeconomic modelling. LEAP can also accommodate a variety of cost-related inputs, which opens the door to a broader set of modelling methodologies (such as optimal dispatch and capacity expansion for power sector modelling). This study does not invoke LEAP's cost modelling capabilities. As a result, any mention of technology costs or financial barriers is part of the narrative description of each scenario only.

Acknowledgements

We thank all the stakeholders and experts interviewed, in particular Christine K, Ifeoma Malo, Luis Carlos Miro Baz and Chineme Okafor.

Disclosure Statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported in part by the Nigeria office of the Heinrich Böll Foundation under [grant number 12331123/18]; Heinrich Böll Stiftung

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References

6WResearch. (2018). *Nigeria diesel genset market (2018–2024)*. New Delhi: Author.

All On. (2016). *Nigeria: Energy needs assessment and value chain analysis*.

Antwi-Agyei, P., Dougill, A. J., Agyekum, T. P., & Stringer, L. C. (2018). Alignment between nationally determined contributions and the sustainable development goals for West Africa. *Climate Policy*, *18*(10), 1296–1312. doi:10.1080/14693062.2018.1431199

Anyaogu, I. (2018, July 11). Sterling bank provides financing for solar energy projects. *Business Day*. Retrieved from https://www.businessdayonline.com/companies/renewables/article/%e2%80%8b%e2%80%8bsterling-bank-provides-financing-solar-energy-projects/

Awofeso, N. (2011). Generator diesel exhaust: A major hazard to health and the environment in Nigeria. *American Journal of Respiratory and Critical Care Medicine*, *183*(10), 1437. doi:10.1164/ajrccm.183.10.1437

Bertheau, P., Cader, C., & Blechinger, P. (2016). Electrification modelling for Nigeria. *Energy Procedia*, *93*, 108–112. doi:10.1016/j.egypro.2016.07.157

Bhatia, M., & Angelou, N. (2015). *Beyond connections: Energy access redefined* (ESMAP Technical Report No. 008/15). Retrieved from World Bank website: https://openknowledge.worldbank.org/handle/10986/24368

Blechinger, P., Cader, C., & Bertheau, P. (2019). Least-cost electrification modeling and planning–a case study for five Nigerian Federal states. *Proceedings of the IEEE* (pp. 1–18). doi:10.1109/JPROC.2019.2924644

Brandt, P., Ernst, A., Gralla, F., Luederitz, C., Lang, D. J., Newig, J., … von Wehrden, H. (2013). A review of transdisciplinary research in sustainability science. *Ecological Economics*, *92*, 1–15. doi:10.1016/j.ecolecon.2013.04.008

CCAC. (2018). SNAP - Supporting national action and planning on SLCPs. Retrieved from https://www.sei.org/wp-content/uploads/2015/05/11.2-ccac-snap-factsheet-nigeria.pdf

Cervigni, R., Rogers, J. A., & Henrion, M. (2013). *Low-carbon development: Opportunities for Nigeria*. doi:10.1596/978-0-8213-9925-5

Climatters. (2018). *Pushing off-grid renewables for micro, small and medium enterprises (MSME) in Nigeria*. Retrieved from https://sun-connect-news.org/fileadmin/DATEIEN/Dateien/New/Edited-SME-Full-Document.pdf

CSEA Africa. (2019). How to resolve the tariff disputes blocking Nigeria's Solar Project Pipeline? Retrieved from http://cseaafrica.org/how-to-resolve-the-tariff-disputes-blocking-nigerias-solar-project-pipeline/

Debnath, K. B., & Mourshed, M. (2018). Challenges and gaps for energy planning models in the developing-world context. *Nature Energy*, *3*(3), 172–184. doi:10.1038/s41560-018-0095-2

de Boer, W. (2018, July 2). Addressing the access-to-energy challenge in Nigeria. *African Business Magazine*. Retrieved from http://africanbusinessmagazine.com/QW8lu

DFID. (2018). *DFID Nigeria*. Retrieved from https://www.gov.uk/world/organisations/dfid-nigeria

DMO. (2017). Green bond. Retrieved from Debt Management Office Nigeria website. Retrieved from https://www.dmo.gov.ng/fgn-bonds/green-bond

ECN. (2014). *National energy masterplan (NEMP)*. Energy Commission of Nigeria.

Emodi, N. V. (2016). *Energy policies for sustainable development strategies: The case of Nigeria*. Retrieved from //www.springer.com/us/book/9789811009730

ERM. (2009). *Impact of climate change on Nigeria's economy*. DFID.

Farquharson, D., Jaramillo, P., & Samaras, C. (2018). Sustainability implications of electricity outages in sub-Saharan Africa. *Nature Sustainability*, *1*(10), 589. doi:10.1038/s41893-018-0151-8

FGN. (2013). *Nigeria post disaster needs assessment 2012 floods*.

FGN. (2015). *Nigeria's Intended Nationally Determined Contribution*. Federal Government of Nigeria.

FGN. (2016). *Nigeria's sustainable energy for all action agenda (SE4ALL-AA)*. Retrieved from Federal Government of Nigeria website: http://www.power.gov.ng/Press%20Release/SUSTAINABLE%20ENERGY%20FOR%20ALL%20ACTION%20AGENDA%20(SEE4ALL-AA).pdf

FGN. (2017). *Nigeria's draft nationally determined contribution (NDC). Implementation action plan for the power sector*. Unpublished. Federal Government of Nigeria.

FMITI. (2014). *Nigeria industrial revolution plan*. Federal Ministry for Industry Trade and Investment.

FMPWH. (2016). *National renewable energy & energy efficiency policy (NREEEP)*. Federal Ministry of Power, Works and Housing.

Future Energy Nigeria. (2017). *Nigeria - a current projects database*.

GCF. (2018a). FP027 Universal green energy access programme. Retrieved from Green Climate Fund website: https://www.greenclimate.fund/projects/fp027

GCF. (2018b). Nigeria - country profiles. Retrieved from Green Climate Fund website: https://www.greenclimate.fund/countries/nigeria

GIZ. (2017). *Methodological approach towards the assessment of simulation models suited for the economic evaluation of mitigation measures to facilitate NDC implementation*. Retrieved from Deutsche Gesellschaft für Internationale Zusammenarbeit website: http://ndcpartnership.org/content/methodological-approach-towards-assessment-simulation-models-suited-economic-evaluation

GIZ NESP. (2015). *The Nigerian energy sector*.

GOGLA, IFC, Berenschot, EforA Coalition, Energy Saving Trust, & CLASP. (2019). *Global off-grid solar market report. Semi-annual sales and impact data*. Retrieved from https://www.gogla.org/global-off-grid-solar-market-report?utm_source=Social&utm_campaign=H22018Sales

Graber, S. (2018). *Under the grid: Improving the economics and reliability of rural electricity Service with undergrid minigrids*. Retrieved from https://rmi.org/insight/under-the-grid/

HBS, & CSJ.. (2017). *Solar energy and the federal budget: 2012*–2016. Heinrich-Böll-Stiftung Nigeria and Centre for Social Justice. Retrieved from https://csj-ng.org/blog/solar-energy-and-the-federal-budget-2012-2016/.

Heaps, C. G. (2016). *Long-range energy alternatives planning (LEAP) system. [Software version: 2018.1.20]*. Retrieved from https://www.energycommunity.org

Heft-Neal, S., Burney, J., Bendavid, E., & Burke, M. (2018). Robust relationship between air quality and infant mortality in Africa. *Nature*, *559*(7713), 254. doi:10.1038/s41586-018-0263-3

Ibrahim, H., & Kirkil, G. (2018). Electricity demand and supply scenario analysis for Nigeria using long range energy Alternatives planning (LEAP). *Journal of Scientific Research & Reports*, *19*(2), 1–12.

IEA. (2017). *World energy outlook 2017: Special report on energy acces - from poverty to prosperity*. Retrieved from http://www.iea.org/access2017/

IEA. (2018). *World energy outlook 2018 - electricity access database*. Retrieved from https://www.iea.org/media/sdg/WEO2018-Electricity-Database.xlsx

IMF. (2018). Nigeria and the IMF. Retrieved from International Monetary Fund website: http://www.imf.org/en/Countries/NGA

IPCC. (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Japan: IGES.

LEAP. (2019). Nigeria power sector pathways dataset. Retrieved from https://www.energycommunity.org/default.asp?action=applications&ID=102.

Markkanen, S., & Anger-Kraavi, A. (2019). Social impacts of climate change mitigation policies and their implications for inequality. *Climate Policy*, *19*(7), 827–844. doi:10.1080/14693062.2019.1596873.

Mathy, S., Fink, M., & Bibas, R. (2015). Rethinking the role of scenarios: Participatory scripting of low-carbon scenarios for France. *Energy Policy*, *77*, 176–190. doi:10.1016/j.enpol.2014.11.002

McCollum, D. L., Echeverri, L. G., Busch, S., Pachauri, S., Parkinson, S., Rogelj, J., … Riahi, K. (2018). Connecting the sustainable development goals by their energy inter-linkages. *Environmental Research Letters*, *13*(3), 033006. doi:10.1088/1748-9326/aaafe3

Mentis, D., Welsch, M., Fuso Nerini, F., Broad, O., Howells, M., Bazilian, M., & Rogner, H. (2015). A GIS-based approach for electrification planning—A case study on Nigeria. *Energy for Sustainable Development*, *29*, 142–150. doi:10.1016/j.esd.2015.09.007

Moksnes, N., Korkovelos, A., Mentis, D., & Howells, M. (2017). Electrification pathways for Kenya–linking spatial electrification analysis and medium to long term energy planning. *Environmental Research Letters*, *12*(9), 095008. doi:10.1088/1748-9326/aa7e18

NERC. (2012, June). The multi year tariff order for the determination of the cost of electricity generation for the period 1st of June 2012-31st May 2017. Retrieved from http://www.nercng.org/index.php/document-library/func-startdown/67/

NERC. (2015). Draft feed-in tariff regulations for renewable energy sourced electricity in Nigeria. Retrieved from https://www.iea.org/media/pams/nigeria/NIGERIA_FIT_regulation2015enteringintoforceFeb2016.pdf

NERC. (2018a). *Quarterly report, second quarter* 2018. Retrieved from Nigerian Electricity Regulatory Commission (NERC) website. Retrieved from http://www.nercng.org/index.php/library/documents/NERC-Reports/NERC-Quarterly-Reports/NERC-Second-Quarter-Report-2018/

NERC. (2018b). Regulations. Retrieved 9 December 2018, from Nigerian Electricity Regulatory Commission website. http://www.nercng.org/index.php/library/documents/Regulations/orderby,7/

Nerini, F. F., Sovacool, B., Hughes, N., Cozzi, L., Cosgrave, E., Howells, M., … Milligan, B. (2019). Connecting climate action with other sustainable development goals. *Nature Sustainability*, *2*(8), 674–680. doi:10.1038/s41893-019-0334-y

Nerini, F. F., Tomei, J., To, L. S., Bisaga, I., Parikh, P., Black, M., … Mulugetta, Y. (2018). Mapping synergies and trade-offs between energy and the sustainable development goals. *Nature Energy*, *3*(1), 10–15. doi:10.1038/s41560-017-0036-5.

NESG, & HBS. (2017). *True cost of electricity: Comparison of costs of electricity generation in Nigeria*. Retrieved from Nigerian Economic Summit Group, Heinrich Böll Foundation Nigeria Office website: https://ng.boell.org/true-cost-electricity

NESG, & RMI. (2018). *Minigrid investment report - scaling the nigerian market*. Retrieved from Nigerian Economic Summit Group (NESG) and Rocky Mountain Institute (RMI) website: https://www.rmi.org/wp-content/uploads/2018/08/RMI_Nigeria_Minigrid_Investment_Report_2018.pdf

NESISTATS. (2018). *Daily briefing on the nigerian power sector - advisory power team, office of the vice president*. Retrieved from https://datastudio.google.com/u/0/reporting/0B2vSlCHmtU3LTUNod0NGWkM5YU0/page/DtOI

NESP. (2017). *Rural electrification plan for five Nigerian states: Plateau, Ogun, Sokoto, Niger, Cross River*. Unpublished. Abuja: Nigerian Energy Support Programme (NESP).

Nextier Power. (2018). Revisiting Nigeria's pending solar IPP Projects: An overview of the situation. Retrieved 31 May 2019, from Nigeria Electricity Hub website: https://www.nigeriaelectricityhub.com/download/revisiting-nigerias-pending-solar-ipp-projects-an-overview-of-the-situation-2/

Occhiali, G., & Falchetta, G. (2018). *The changing role of natural gas in Nigeria* (SSRN Scholarly Paper No. ID 3149339). Retrieved from Social Science Research Network website: https://papers.ssrn.com/abstract=3149339

Office of the VP, & Power Africa. (2015). *Nigeria power baseline report*. Retrieved from Advisory Power Team, Office of the Vice President in conjunction with Power Africa website: http://www.nesistats.org/uploads/3/4/9/3/34934878/ner.pdf

OGEF. (2018). The off-grid energy access fund. Retrieved from https://www.ogefafrica.com

Oguntoke, O., & Adeyemi, A. (2017). Degradation of urban environment and human health by emissions from fossil-fuel combusting electricity generators in Abeokuta metropolis, Nigeria. *Indoor and Built Environment*, *26*(4), 538–550. doi:10.1177/1420326X16629818

Ohiare, S. (2015). Expanding electricity access to all in Nigeria: A spatial planning and cost analysis. *Energy, Sustainability and Society*, *5*, 1. doi:10.1186/s13705-015-0037-9

Oladokun, V. O., & Asemota, O. C. (2015). Unit cost of electricity in Nigeria: A cost model for captive diesel powered generating system. *Renewable and Sustainable Energy Reviews*, *52*, 35–40. doi:10.1016/j.rser.2015.07.028

Osunmuyiwa, O., Biermann, F., & Kalfagianni, A. (2018). Applying the multi-level perspective on socio-technical transitions to rentier states: The case of renewable energy transitions in Nigeria. *Journal of Environmental Policy & Planning*, *20*(2), 143–156. doi:10.1080/1523908X.2017.1343134

Oxfam America. (2017). The energy challenge in sub-Saharan Africa. Retrieved from https://www.oxfamamerica.org/explore/research-publications/the-energy-challenge-in-sub-saharan-africa/

Oyewo, S., Aghahosseini, A., & Breyer, C. (2017). *Assessment of energy storage technologies in transition to a 100% renewable energy system for Nigeria*. 11th international renewable energy storage Conference.

Palazzo, A., Vervoort, J. M., Mason-D'Croz, D., Rutting, L., Havlík, P., Islam, S., … Zougmore, R. (2017). Linking regional stakeholder scenarios and shared socioeconomic pathways: Quantified West African food and climate futures in a global context. *Global Environmental Change*, *45*, 227–242. doi:10.1016/j.gloenvcha.2016.12.002

Power for All. (2019). *Power for all factsheet. decentralized renewable energy and SDGs in Nigeria*. Retrieved from https://www.powerforall.org/resources/fact-sheets/fact-sheet-nigeria-dre-sdg-nexus

Practical Action. (2018). *Poor people's energy outlook*. Retrieved from Practical Action website: https://policy.practicalaction.org/policy-themes/energy/poor-peoples-energy-outlook/poor-people-s-energy-outlook-2018

PwC. (2016). *Powering nigeria for the future*.

RMI, & REA. (2018). *A design charrette to achieve 20c/kWh by 2020 - pre-read document*. Rocky Mountain Institute and Rural Electrification Agency.

Rogelj, J., Elzen, M. d., Höhne, N., Fransen, T., Fekete, H., Winkler, H., … Meinshausen, M. (2016). Paris Agreement climate proposals need a boost to keep warming well below 2 °C. *Nature*, *534*(7609), 631–639. doi:10.1038/nature18307

Roy, P., & Ibrahim, J. (2018). Power in Nigeria: Increasing generating capacity in the Nigerian power sector by reducing incentives for capture [Anti-Corruption Evidence (ACE)]. Retrieved from https://ace.soas.ac.uk/power-in-nigeria/

Schmid, E., & Knopf, B. (2012). Ambitious mitigation scenarios for Germany: A participatory approach. *Energy Policy*, *51*, 662–672. doi:10.1016/j.enpol.2012.09.007

SEforALL. (2018). *Energizing finance* 2018. Retrieved from https://www.seforall.org/EnergizingFinance

SERAP. (2017). *'From darkness to darkness' - How Nigerians are paying the price for corruption in the electricity sector*. Retrieved from Socio-economic rights and accountability project (SERAP) website: http://serap-nigeria.org/wp-content/uploads/2017/08/CORRUPTION-IN-ELECTRICITY-REPORT-A4.pdf

Solar Plaza. (2017). *Establishing a foothold in the Nigerian solar PV market*. Retrieved from https://www.solarplaza.com/channels/markets/11771/establishing-foothold-nigerian-solar-pv-market/

SUNREF. (2018). AFD supports the Nigerian banking sector with SUNREF. Retrieved from https://www.sunref.org/en/afd-supports-the-nigerian-banking-sector-with-sunref/

TCN. (2018). *Transmission expansion plan development of power system master plan for the transmission company of Nigeria*. Transmission Company of Nigeria website Retrieved from https://tcnpmu.ng/transmission-expansion-plan-development-of-power-system-master-plan-for-the-transmission-company-of-nigeria/

TCN PMU. (2017). *Nigeria power sector recovery plan - transmission infrastructure gap analysis.* Unpublished. Transmission Company of Nigeria.

UNDESA. (2017). *World population prospects: The 2017 revision, key findings and advance tables* (No. ESA/P/WP/248). Retrieved from https://esa.un.org/unpd/wpp/Publications/

UNDESA. (2018). *World urbanisation prospects* 2018. Retrieved from https://esa.un.org/unpd/wpp/Publications/

UNIDO. (2016). *World small hydropower development report* 2016. Retrieved from https://www.unido.org/sites/default/files/2016-11/WSHPDR_Executive_Summary_2016_0.pdf

Verisk Maplecroft. (2013). Climate change and environmental risk atlas. Retrieved from https://maplecroft.com/about/news/ccvi_2013.html

Verolme, H. (2017). Peoples' power or how to ensure access to affordable, reliable, sustainable and modern energy for all. *Spotlight on sustainable development, reflection group on the 2030 agenda for sustainable development*. Retrieved from https://www.2030spotlight.org/en/book/1165/chapter/7-peoples-power-or-how-ensure-access-affordable-reliable-sustainable-and-modern

Waisman, H., Bataille, C., Winkler, H., Jotzo, F., Shukla, P., Colombier, M., & Buira, D. (2019). A pathway design framework for national low greenhouse gas emission development strategies. *Nature Climate Change*, *9*(4), 261–268. doi:10.1038/s41558-019-0442-8.

Wiebe, K., Zurek, M., Lord, S., Brzezina, N., Gabrielyan, G., Libertini, J., … Westhoek, H. (2018). Scenario development and foresight analysis: Exploring options to inform choices. *Annual Review of Environment and Resources*, *43*(1), 545–570. doi:10.1146/annurev-environ-102017-030109

World Bank. (2016a). *Achieving universal access in the Kaduna electric service area*. Retrieved from The World Bank website: http://documents.worldbank.org/curated/en/782491487138851242/Achieving-universal-access-in-the-Kaduna-electric-service-area

World Bank. (2016b). RISE – regulatory indicators for sustainable energy. Retrieved from The World Bank website: http://documents.worldbank.org/curated/en/538181487106403375/Regulatory-indicators-for-sustainable-energy-a-global-scorecard-for-policy-makers.

World Bank. (2018a). Nigeria data bank. Retrieved from https://data.worldbank.org/country/nigeria

World Bank. (2018b). Nigeria electrification project. Retrieved from http://projects.worldbank.org/P161885/?lang=en&tab=overview