The Burden of the Broken Grid: Modelling improved power-sector reliability to support low carbon development in Nigeria

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Research Article

Keywords: OSeMOSYS, FlexTool, Nigeria, Nationally Determined Contribution, system reliability

Posted Date: April 12th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2753971/v1

Abstract

Nigeria has one of the greatest electricity deficits globally and, even in areas connected to the central grid, struggles to provide reliable power across the nation. Frequent system collapses and widespread reliance on diesel generation present a burden for Nigerian households and the economy as a whole. One causal factor in these collapses is capacity inadequacy owing to reduced plant availability as plants are frequently non-operational due to maintenance or other management issues. While this dynamic has been established, it has not yet been explored in energy systems modelling as a potential barrier to meeting Nigeria's decarbonization goals. Using a combination of OSeMOSYS and FlexTool modelling, this study shows that increasing available capacity decreases loss of load in the energy system. The resulting decrease in backup diesel generation nearly halves total system costs and emissions. Further, Nigeria is unable to meet its 2021 Nationally Determined Contributions (NDCs) without such improvements, indicating that increasing plant availability and reducing diesel generator use must be prioritized in policy to support national implementation of these targets.

Policy Insights:

1) Improved power plant availability can dramatically reduce CO2 emissions from the power sector, even under a business-as-usual scenario. However, increasing the pace of that improvement has a smaller impact on emissions.

2) Nigeria can meet its 2030 Unconditional NDC targets without significant changes to its generation mix if plant availability is improved. Near-term investments in energy efficiency will help to further ensure that targets are met.

3) Nigeria can meet its 2030 Conditional NDC targets with energy efficiency investments and improved plant availability.

4) A 30% cap on variable renewable energy (VRE) coupled with full plant availability is expected to reduce system collapses and lost loads. In the flexibility analysis, runs with full availability were able to reduce lost load even in scenarios with increased VRE.

5) It is not possible to meet long-term decarbonization goals without plant improvement.

1. Introduction And Research Objectives

While Nigeria has the largest population of any African nation, the available generation capacity for the country sits far below that of many other nations, at just 6.7 GW reliably connected to the grid (Nigerian Electricity Regulatory Commission, 2021). This capacity is dominated by gas power plants which are frequently out of service due to maintenance or fuel constraints (Daggash & Mac Dowell, 2021). The unreliability of the fleet and the grid itself mean that the nation experiences frequent blackouts (Soyemi et al., 2021; Oyedepo, 2012). For many Nigerians, the lack of reliable grid power means that backup generators are a part of daily life: over 86% of businesses and nearly a quarter of households own a generator (Oseni, 2016; IFC, 2019). Persistent system failures and the prevalence of diesel generation come with significant development impacts, as power system inadequacy is estimated to create annual GDP losses of 6% or USD 22.8 Billion (Power for All, 2019).

On top of the on-grid emissions from fossil fuel generation, emissions from diesel generation are likely to be a serious hurdle in meeting the country's latest Nationally Determined Contribution (NDC) (Federal Government of Nigeria, 2021). Further, the unreliability of the current generation fleet, if not addressed, raises questions about the flexibility of the system. This will determine its ability to handle the increasing penetration of variable renewable energy (VRE) needed to meet the NDC decarbonisation target.

While other studies have modelled the Nigerian energy system, none have yet evaluated the country's ability to meet the latest round of NDCs. Further, in the body of published work there is little optimization modelling that explores diesel generation or the persistent issues with plant availability. The flexibility of the system given these variables is also yet to be explored.

This leads to a key, as yet unanswered, question: how will Nigeria balance its grid reliability issues and the resulting reliance on diesel generation with its climate commitments? This study aims to answer that question using energy systems modelling to explore the impacts of improved plant availability on alternative pathways for the development of Nigeria's power sector. Given the context presented above (and further explored in Section 2), these impacts primarily centre around system adequacy and emissions/costs of diesel generator use. Ultimately, this analysis will synthesize these impacts and explore their implications for meeting the nation's development targets, including the latest NDC.

The current power system in Nigeria is described in the first part of Section 2, while the remainder of the section is devoted to a discussion of previous modelling work. Section 3 describes the methodology used in this study, including any assumptions and data used in the modelling. Section 4 presents the results from both the OSeMOSYS and FlexTool models, which show that increased plant availability reduces loss of load and consequently is anticipated to reduce generator usage. Further, reduced reliance on self-generation is found to nearly halve emissions and system costs. Section 5 compares the results to previous work and analyses the feasibility of improvements assumed in the modelling, along with the implications of each development pathway for meeting NDC targets. Finally, Section 6 summarizes key findings and implications for policymaking .

2. Background And Literature Review

2.1 Nigeria's Current Power System and Business-As-Usual Impacts

Nigeria's power system is dominated by gas power plants which make up 80% of the on-grid generation capacity, with the remaining 20% made up of hydropower. While these plants represent 13,014 MW of generation capacity, actual generation has never surpassed 6,000 MW (Transmission Company of Nigeria, 2022). The generation shortfall can be largely attributed to low plant availability – capacity is considered unavailable when it cannot be used to reliably generate power. Availability can be constrained by a variety of factors, including lack of preventative maintenance, inadequate gas supply to plants, water shortages, vandalism, and transmission constraints (Daggash & Mac Dowell, 2021). Figure 1 shows the 2019 available capacity which is roughly 43% of the installed capacity.

Loss of plants to maintenance issues cannot solely be attributed to the age of the fleet as Nigeria's gas plants are an average of 12.6 years old, approximately halfway through their lifespan (Nigerian Electricity Regulatory Commission, 2018). The average age of gas fleets in many other developed countries is much older; for instance, the UK's gas fleet is 22.4 years old (BEIS, 2022). Further, the 2019 available capacity of the five newest gas plants in Nigeria (added between 2015–2018) is 64% of their rated capacity. This is not far above the overall fleet average of 43% and far below the international standard (Nigerian Electricity Regulatory Commission, 2021; Oyedepo et al., 2014). Surveys of gas plants in the nation largely point to poor maintenance culture, insufficient supply of spare parts, and funding issues as causal factors for plant downtime (Oyedepo et al., 2014). In terms of options for improvement, regular preventative maintenance of plants as well as improved tariff structures to reinforce cost-effective practices may help to target these issues (Oyedepo et al., 2014; Soyemi et al., 2021).

These plant and grid management issues result in semi-frequent system collapses; there have been seven so far in 2022 and a trend of ten or more such collapses per year in the last decade (Jeremiah & Akubo, 2022; Justin et al., 2021). Given the frequency of blackouts, backup diesel-powered generation has emerged as a key resource for maintaining access to electricity in both the industrial and residential sectors. Estimates indicate that "over 86% of businesses and almost a quarter of homes have generators" and that installed capacity is between 15 and 20 GW (Oseni, 2016:p.246; IFC, 2019). These estimates put the generator capacity equal to or nearly double the installed on-grid capacity.

Due to high diesel prices, electricity produced by these diesel generators is twice as expensive as power supplied by the grid (Advisory Power Team & Power Africa, 2015). Reliance on self-generation in the industrial sector is estimated to add 30% of the price of domestic products over imports (FMITI, 2014). Failing to address system management issues in the nation will reinforce this reliance on self-generation and continue to weigh down Nigerian homes and businesses with the cost of supplying their own electricity.

The use of diesel generators also creates emissions with significant climate and health impacts for the nation. One study estimated that diesel generation in Nigeria "produces CO2 emissions equivalent to 60% of its annual electric sector emissions" (Farquharson, 2019:p.25). This is largely attributed to the low efficiency of generators when compared to traditional power plants. In sub-Saharan Africa, emissions from diesel generation also likely account for the "majority of power sector emissions of nitrogen oxides (NOx) and fine particulate matter (PM2.5)" as generators produce higher amounts of these pollutants per KWh than many typical generation sources (IFC, 2019:p.vi). Due to the proximity of generators to homes, the high PM emissions are particularly worrisome for local air quality and the health of Nigerians.

2.2 The Renewable Energy Opportunity in Nigeria

Despite the current dominance of fossil generation, Nigeria boasts an abundance of renewable resources. Technical potentials for solar (32,456 TWh) and wind (10,140 TWh) are respectively sixty and eighteen times larger than anticipated demand in 2050 (Allington et al., 2022). Hydropower is the only renewable resource currently exploited at a large scale. The 1,990 MW installed capacity is roughly 14% of the estimated technical potential of 14,120 MW (Pappis et al., 2019). Given this resource availability, the predominant struggle for the nation is the incentivisation of renewable energy development and its reliable integration into the grid.

In this vein, recent national policies and international commitments stress the importance of reducing emissions and increasing the use of renewables. Nationally, the National Renewable Energy and Energy Efficiency Policy (NREEEP) outlines a broad commitment to green development and the Vision 30:30:30 targets set goals for renewable generation. The primary target in Vision 30:30:30 is the generation of "30,000MW of electricity by the year 2030 with renewable energy contributing 30 per cent of the energy mix" (Federal Government of Nigeria, 2016).

Nigeria has also signed on to the Paris Agreement and has committed to long-term decarbonisation. The 2021 update to their conditional and unconditional NDCs reiterated this commitment and further reduced their emissions ceiling. These updates incorporated more pollutants in the emissions calculations and used a less aggressive growth rate, in-line with observed growth from 2015-2021 (Federal Government of Nigeria, 2021). The new growth rate led to lower BAU emissions projections (452 MT versus 898 MT), but the nation has maintained its unconditional commitment of 20% below BAU by 2030. The conditional commitment has been increased to 47% below BAU (up from 45%). Given lower BAU estimates, these updated commitments represent lower actual emissions limits. These goals present ambitious green development targets requiring significant investment and thoughtful implementation.

Out of the policies surveyed above, only the supporting targets outlined in the Conditional NDC address the issue of backup diesel generation directly. Even then, the target simply specifies the “elimination of diesel self-generation by 2030” without any supporting objectives (Federal Government of Nigeria, 2021). So, despite the significant role of diesel generation it remains largely absent from Nigeria’s national and international commitments to green development.

2.3 Previous Modelling of Nigeria’s Power System

Several studies have modelled the Nigerian energy system in the last decade through a broad range of lenses. Given the electricity access and grid issues in the nation, a number have focused on the “electricity gap” and the nation’s ability to meet growing demand. Avila et al. (2017), Ibrahim and Kirkil (2018), and Dada and Moser (2019) all explore this issue, but their scenarios have an explicit focus on on-grid technologies and do not consider the current or anticipated future role of self-generation in the energy mix. Their modelling anticipates that the expansion of on-grid capacity can meet growing demand but do not address plant availability. These studies also all appear to use current installed capacity as the baseline in models. As addressed above, even newer plants are subject to availability issues and the expansion of capacity alone is unlikely to solve reliability issues in the nation.

Other recent models have explored Nigeria’s initial NDC commitments but do not account for the COP26 updates or devote significant attention to diesel generation. Roche et al. (2020) explore trade-offs between meeting Nigeria’s first round of NDC targets on top of its development and electricity access goals. In each of the scenarios explored, Nigeria can meet its initial NDC despite significant levels of diesel self-generation.

Dioha and Kumar (2020) also explore the 2015 NDC with a TIMES optimization model and find that Nigeria can meet its NDC targets with a mix of solar, hydro, gas, and diesel generators. Their scenarios have less diesel than those presented by Roche et al., but they are once again modelled as a part of a decentralized grid rather than as backup generation for the main grid (Dioha & Kumar, 2020:p.33). This is qualified by the fact that improvements in the central grid are said to reduce the share of demand on the decentralized grid – indicating that the modelling does account for improvements in the central grid which reduce reliance on diesel, but the nature of these improvements is unclear.

Daggash and Mac Dowell (2021) found that Nigeria would be able to deliver its initial NDC targets with no added costs versus business-as-usual (BAU). This study used highly granular data and was able to model regional grid connections which provided further insight into the political and economic feasibility of their scenarios. The scenarios modelled did include significant amounts of diesel in the initial model period but diesel fades from the generation mix by 2030 and appears again later in the model period. From the modelling it is unclear if improvement in plant performance is the reason for this decrease or if capacity expansion alone makes up for increased on-grid generation.

To summarize, existing modelling of the Nigerian system is interested in the energy gap and in energy efficiency but does not specifically focus on the issue of self-generation in the absence of reliable on-grid power. When diesel generation has been explored, it has mostly been explored in the context of an off-grid technology rather than explicitly connected to the issue of plant availability and the reliability of the power grid.

2.4 Research Gap and Rationale

The background and literature review above have showcased the widespread reliance on diesel generation which can be traced back to persistent reliability issues with the Nigerian grid. The impacts of the reliance on self-generation can be felt nationally when it comes to emissions, but this reliance also has significant economic and health impacts for individual households. Previous modelling work has not yet explored this dynamic between plant availability and backup generation for homes already connected to the grid. This study aims to model this dynamic and how it may impact the newest round of NDC commitments which have also yet to be modelled. Drawing from the findings in previous work, modelling will also explore the role of EE. Further, few studies have incorporated flexibility modelling for the country, and developing such a model with an open-source tool like FlexTool can serve as an important stepping stone for future work.

3. Methodology

3.1 OSeMOSYS and FlexTool

OSeMOSYS is a bottom-up energy systems model which optimizes system costs for a given set of technologies and demands. The set of demands, fuels, and technologies used in this study are outlined in the reference energy system presented in Figure 2. As shown, end-use demands in this study are not exogenously split between on and off grid, rather the model may choose to expand the grid when cost-effective versus off-grid generation.

OSeMOSYS was chosen for this study primarily for its low data and computing requirements, existing data ecosystem, and open-source format. Open-source code and “Starter Data Kits” reduce the time needed to build a model and increase the accessibility of this and other models so that they may be built upon in future work.

The OSeMOSYS dataset used in this study is built from the base file described in Allington et al. (2021) with some adjustments and further assumptions outlined below. The data files are also built to work with the cloud-based ClicSAND 3.0 interface (Cannone et al., 2022).

Given the focus on system reliability, OSeMOSYS is limited in its representation of time, especially for projects with limited computing resources such as this. The model used here simplifies a year into four seasons and eight timeslices to represent a day and night in each season. To overcome this issue and to add depth to the analysis, OSeMOSYS results were put into the International Renewable Energy Agency’s FlexTool to further analyse the hourly flexibility and adequacy of the resulting generation mix.

FlexTool is another open-source tool which models an energy system’s ability to meet hourly demand each year. Key inputs include reserve margin as well as capacities and technical data of generating technologies. The model then outputs the anticipated loss of load, capacity inadequacy, and VRE curtailment (IRENA, 2019). Here, the model is used to validate the OSeMOSYS scenarios and to explore the flexibility tradeoffs associated with persistent plant availability issues.

3.2 OSeMOSYS Inputs: Current Power System Data

As outlined before, Nigeria’s power system is dominated by gas power plants with a few large hydropower projects. Active plants were identified using historic power sector data from the Nigerian Electricity Regulatory Commission (Nigerian Electricity Regulatory Commission, 2020, 2021, 2018). Table 1 shows the installed capacity of each technology in 2021.

Table 1. 2021 Installed generation capacity.

Data from NERC (2018, 2021) and GEM (GEM, 2022)

Technology	2021 Installed Capacity (GW)
Gas (CCGT)	4.738
Gas (SCGT)	6.721
Large Hydropower (>20 MW)	1.99
Diesel	17.9
Off-Grid Solar PV	0.0264
Micro Hydro (<1 MW)	0.0004

Power plants and renewables projects currently under construction were also included in the residual capacity in the model and have been set to start generating in line with expected commissioning dates as per the Global Energy Monitor (Global Energy Monitor, 2022).

The exact installed diesel generation capacity in Nigeria remains unknown, but estimates project that approximately 8–14 GW were in use in 2016, 10–15 GW in 2017, and 2019 capacity was in the range of 15–20 GW (Federal Government of Nigeria, 2016; REA, 2017; IFC, 2019). To estimate the existing capacity used in this study, the medians of these estimates were used for their respective years and the average growth between estimates was used to estimate capacity in the remaining years. After initial model runs, capacity was refined to fill unmet demand given historical generation data from 2015–2021.

Generation of on-grid technologies is limited by this same generation data from the first seven years in the modelling period (2015–2021). During this initial model period, investment in transmission capacity is also constrained to current and historic capacity.

3.3 OSeMOSYS Inputs: Techno-economic Assumptions

Other key techno-economic assumptions include a discount rate of 10% and reserve margin of 15%, consistent with previous modelling studies (Dioha & Kumar, 2020; Daggash & Mac Dowell, 2021). Costs, technology lifetimes, transmission losses, and capacity factors were taken from Allington et al. (2022). Renewable energy potentials and fuel reserves were also taken from this dataset with the exception of hydropower potential which used a conservative estimate which considered only operational and planned hydropower projects as opposed to technical potential[1].

To minimize flexibility issues on the already fragile grid, utility-scale VRE generation was limited across all scenarios to 30% of demand each year with 20% coming from wind and 10% coming from solar. This cap is in line with IRENA modelling of the West African Power Pool which used the same penetration caps to ensure system reliability across scenarios (IRENA, 2013).

3.4 Efficiency Technologies

While demand is exogenously defined in OSeMOSYS, efficiency technologies used in this model do allow investment in EE to reduce the overall demand to be met by generating technologies. As in Allington et al. (2022), each efficiency technology is modelled to generate a small amount of power to offset the efficiency gains assumed to come from using an efficient appliance to fulfil an energy service. Highly efficient appliances are assumed to be 30% more efficient than the baseline while moderately efficient appliances are assumed to be 15% more efficient.

3.5 Scenarios

Four base scenarios were modelled (see Table 2) to explore the impacts of BAU practices and pathways to meet Nigeria's 2021 NDC commitments.

Table 2. Core scenarios used in modelling.

Scenario	Description and Constraints
BAU	On-grid investment is constrained to only natural gas and hydropower. No investment in EE.
Least Cost (LC)	Minimal constraints to find least-cost solution. No investment in nuclear power but investment in all other technologies is unconstrained. Gradual investment in EE.
Unconditional NDC (UNDC)	Emissions capped at 20% below BAU emissions in 2030 (85.3 MT) from 2030 onwards. Gradual investment in EE.
Conditional NDC (CNDC)	Emissions capped at 47% below BAU emissions in 2030 (56.5 MT) from 2030 onwards. All SCGTs are phased out by 2030. 13 GW off-Grid renewables, 3.5 GW of small hydro, and 12 GW of new large hydro capacity added by 2030. Transmission and distribution (T&D) losses improve to international standard by 2030. Gradual investment in EE.

Where scenarios include gradual investment in energy efficiency, investment is constrained to 5% of the 2050 capacity deployed in a run without any efficiency constraint as in Cannone et al. (2023)[2].

3.6 Variation in Model Runs

Each scenario was also run with three different timescales for plant availability improvement associated with improved management practices: improvement to 2030, 2050, and no improvement. The primary assumption here is that any load not met by on-grid plants due to low plant availability will be met by diesel generation. The availability factors by technology can be found below in Table 3. These factors represent the percentage of the installed capacity of a technology that can be reliably called upon to generate power.

Table 3. Availability factors.

Data calculated using NERC (2021, 2018).

	Baseline Availability (no improvement)	Annual Improvement to 2030	Annual Improvement to 2050
Combined Cycle Gas Turbine	40%	8%	2%
Single Cycle Gas Turbine	47%	7%	2%
Other Fossil	50%	6%	2%
On-Grid Hydropower	68%	4%	1%
Other Renewables	80%	3%	1%

This variation creates the 21 model runs discussed below.

3.7 Flexibility Analysis

This study uses a single-node FlexTool model with primary inputs derived from the OSeMOSYS modelling. The reserve margin (15%) and costs and efficiencies of technologies are the same as was used for the OSeMOSYS modelling (sourced from Allington et al. 2022)[3]. The updated demand for scenarios with EE and the capacity of each technology were taken directly from the results. Only the available capacity for each model run was added to FlexTool and diesel capacity was not included as FlexTool focuses on-grid generation and diesel capacity is assumed to be used for backup generation.

As FlexTool explores the flexibility of a system over a single year, the flexibility analysis presented here focuses on model year 2040. Exploring model results in 2040 exposes the impacts of a range of different availability factors: the runs with 2030 improvement will be at 100% while the 2050 runs will be higher than the baseline but not quite at 100%, while the BAU runs will be at baseline. Under the UNDC and CNDC constraints, 2040 also represents a challenging year where demand continues to grow despite emissions caps.

[1] Further information on the input data used in modelling be found in Appendix A.
[2] For additional information on these constraints see Appendix B.
[3] Additional details on the input data used in the FlexTool modelling can be found in Appendix C.

4. Results And Analysis

Results from modelling the Nigerian energy system are presented below from 2015–2065 with the model period running until 2070 to account for end-game optimization issues at the end of the model period which are typical of bottom-up optimization models. Out of the twelve model runs, three runs produced a generation shortfall, deploying the model's backstop. This backstop is included as a very expensive technology with unconstrained capacity that the model can deploy if it is unable to meet demand in any scenario to keep the model from failing. Table 4 shows the runs with backstops and the size of the shortfall in TWh. To contextualise these figures, the current (2022) electricity demand is 81 TWh and is expected to rise to 919 TWh in 2065 (Allington et al., 2021). This shortfall is additional to the shortfall met by diesel generation and is due to emissions constraints in NDC scenarios.

Table 4. Generation shortfall in model runs.

	BAU	Least Cost	UNDC	CNDC
Improvement to 2030	OK	OK	OK	OK
Improvement to 2050	OK	OK	14 TWh	OK
BAU/No Improvement	OK	OK	2,314 TWh	1,381 TWh

Across scenarios, the generation results presented below show that increased plant availability decreases the use of diesel generators. Increased availability also reduces total system costs and emissions; however, the pace of the improvement (to 2030 versus 2050) has a much smaller impact on both costs and emissions.

However, in the near term it is possible for Nigeria to meet its NDCs with little or no change to its generation mix if plant availability is improved.

4.1 Generation

Business-As-Usual

As Figure 3 shows, capacity is dominated by CCGTs in the model runs with plant improvement to 2030 and 2050. SCGTs, which are the current dominant form of turbine, are phased out after 2040 in all scenarios. In the scenarios with improvement in plant availability, diesel generation is phased out once plants reach full availability. Without improvement, diesel remains an important part of the generation mix (30-50% of generation) throughout the model period.

Hydropower does not come close to its technical potential of 64.3 TWh of annual generation, and peaks at 15 TWh of generation from in 2030. Decentralised PV takes over 4% of generation in 2050 in all scenarios and capacity peaks in 2062 with 22.875 GW installed across model runs.

As no investment in EE is allowed in BAU, variation in the total amount of electricity generated is due to the mix of on/off grid generation — scenarios with high amounts of diesel need to generate less as less energy is lost to the low T&D efficiency.

Least Cost

The least cost generation mix, shown in Figure 4, also includes high amounts of natural gas which is largely made up of CCGTs with SCGT capacity declining after 2025. Biomass also plays a significant role from 2035 onwards and ultimately makes up for 27% of power generated in 2065 in most runs. Coal enters the generation mix after 2025 and remains a stable part of the generation mix until the end of the model period.

The renewable energy mix includes similar amounts of hydropower to the BAU scenario. Onshore wind also plays a small role in the generation mix with utility-scale PV supplying 10% of power generated in 2050 across most model runs.

Diesel generation varies significantly across model runs with higher rates of diesel in runs without availability improvement. Greater variation in the generation mixes and investment in EE mean that diesel generation is lower in Least Cost model runs than in the BAU runs. As was seen in the BAU model, in runs with availability improvement diesel generation is phased out before plant availability reaches target levels.

UNDC

Only one UNDC run, the run with 2030 improvement, could successfully meet demand without surpassing emissions targets. In all other runs, the model's backstop kicked in indicating that no technologies available would be able to meet demand given the constraints on the model. The results for these “failed” runs are presented but the backstops are indicated, and the power generated by backstops is assumed to come from diesel self-generation.

CCGTs remain an important part of the generation mix in the UNDC model runs with SCGTs playing smaller role and disappearing from the mix after 2040. Coal is the only other centralized fossil resource in the model runs but coal generation is roughly half of what it was in the Least Cost runs.

The model invests aggressively in nuclear from 2029 onwards and this makes up 16% of generation in 2050 across runs. Hydropower hits its investment limit in 2054. On-grid solar hits its production limit in 2040 and wind hits its limit in 2050. Off-grid PV is largely absent across model runs until 2050 where it supplies 4-5% of electricity generated.

Even in scenarios without improvement, diesel generation makes up less of the annual power generated in UNDC model runs than in Least Cost or BAU runs.

CNDC

Only two CNDC runs were able to run without backstops — the runs with availability improvement to 2050 and 2030. It is likely that more of the CNDC runs were successful than the UNDC runs (despite the lower emissions limit) due to the forced investment early in the model period in off-grid renewable energy which lessens the on-grid load.

As per scenario constraints and NDC targets, SCGTs phase out of generation by 2030 but CCGTs generate throughout the model period. As seen in Figure 6 coal does enter the generation mix in 2030 but at half the level observed in UNDC runs. As was observed in UNDC model runs, nuclear is deployed to the fullest extent permitted as are wind and solar.

Across all models runs, the level of diesel generation is slightly below the corresponding run's generation in the UNDC by an average of 3%.

4.2 Emissions and NDC Targets

As shown in Figure 7, the BAU model run without availability improvement has the highest emissions overall, followed by the Least Cost run without availability improvement. The UNDC and CNDC model runs have the lowest total emissions over the model period, even when energy generated by the backstop is assumed to be generated by diesel generators.

Across all scenarios, runs with no availability improvement have consistently higher emissions – an average of 45% above those with improvement across scenarios. There are also smaller differences in emissions between runs with 2030 improvement versus runs with 2050 improvement. A slower rate of plant improvement increases total emissions by an average of 2% over the model period.

When emissions are plotted over time, as shown in Figure 8, most scenarios have consistent emissions (within 100 MT CO2e of each other) until 2034 where results begin to diverge more dramatically. In the period of 2030–2035 the Least Cost run without availability improvement surpasses the annual emissions of the BAU scenarios with improvement. In 2065, all Least Cost runs have annual emissions higher than the two BAU model runs with availability improvement. This difference between the LC and BAU scenarios is likely due to the deployment of biomass in the Least Cost runs after 2035.

Despite these changes, later in the model period all Least Cost runs with availability improvement are able to hit the 2030 UNDC target, as shown in Figure 9. The BAU run with full plant availability in 2030 also remains below the emissions threshold. Notably, no viable model runs without availability improvements can hit the NDC targets. The CNDC model runs without improvement are able to hit the targets, but these results are qualified by the fact that these savings early in the model period are likely reflective of insufficient investment, as scenarios are not able to meet demand later in the model period.

4.3 System Costs

Figure 10 shows the total discounted system costs from 2022–2065 across scenarios and model runs. Runs with backstops activated do not have costs shown as the high cost of the backstop technologies skews the costs in the run. Costs include all CAPEX, fuel costs, operational costs, costs of improved energy efficiency, and T&D expansion costs. Notably, the costs of improved plant performance are not included.

As expected, the Least Cost scenarios have the lowest discounted total system costs when compared with the relevant corresponding runs of other scenarios. The cheapest scenario overall is the Least Cost run with availability improvement to 2030 – at USD 149 billion – as this scenario has the least constrictive constraints.

Across scenarios, system costs decrease by an average of 45% as plant availability improves gradually to 2050. This equates to average savings of USD 138 billion over the modelling period. The difference between runs with improvement to 2030 versus 2050 is much lower – a slower rate of improvement only raises system costs by an average of 14%.

4.5 Flexibility

Across scenarios, increased available capacity reduced loss of load. The BAU run without availability improvement had the highest loss of load in 2040, with 41% of demand not met. The three other runs without improvement had the next highest losses as shown in Table 5.

Table 5. Key flexibility metrics.

	Loss of load (% of demand)	Insufficient reserves (% of reserve)	Peak net load (GW)	Available Dispatchable Capacity (GW)
BAU with Improvement to 2030	0.04	7.402	48.54	51.58
BAU with Improvement to 2050	3.39	31.15	48.70	40.93
BAU with No Improvement	41.05	99.63	48.99	21.75
LC with Improvement to 2030	0	0	40.65	49.24
LC with Improvement to 2050	0.07	7.801	38.25	41.46
LC with No Improvement	10.72	68.14	37.46	24.72
UNDC with Improvement to 2030	1.00	14.35	35.12	36.41
UNDC with Improvement to 2050	3.15	20.06	34.13	31.07
UNDC with No Improvement	15.53	89.07	34.56	20.69
CNDC with Improvement to 2030	0.83	13.31	35.23	43.62
CNDC with Improvement to 2050	3.53	20.21	34.52	36.30
CNDC with No Improvement	9.53	52.38	31.72	24.82

Entries in red indicate instances where the peak net load is greater than the available dispatchable capacity, leading to loss of load.

Some loss of load comes from ramp rate limitations in the modelled generation mix, but most of the losses appear to be caused by a lack of capacity. This can be seen in Figures 11 and 12 which present load curves for the first week of the analysis in 2040. These curves show that demand sharply increases each afternoon (between 16:00 and 18:00) and that dispatchable generation is at first able to ramp fast enough to match the demand curve. However, as the capacity is exhausted and the generation curve plateaus, energy supply is unable to keep up with demand.

This inadequacy can also be seen in Table 5 which shows key flexibility indicators, including the peak net load for the year and available capacity. The peak net load is the demand less the amount of VRE generation, and the available dispatchable capacity is the capacity that can be used to meet the remaining demand. This net load is 10 to 20 GW more than the available capacity in some scenarios.

In all scenarios other than BAU, the annual lost load in FlexTool is greater than the diesel generation in the OSeMOSYS modelling by 2–10 TWh. This indicates that the OSeMOSYS modelling does slightly underestimate the supply gap filled by self-generation. Despite this difference, the results from the two models are broadly consistent – improved availability does improve the system adequacy (as shown in the FlexTool results) and reduces the reliance on diesel generation, building a more resilient system.

Likely due to the cap on VRE, there was minimal curtailment across runs. The CNDC run had the highest curtailment with 0.3 to 0.7% of VRE curtailed. Given this VRE limit and use of natural gas in all scenarios, the inertia across scenarios is also not an issue, with zero instances of insufficient inertia in any scenario.

Broadly, the results of the flexibility analysis support the OSeMOSYS modelling in stressing the importance of improved availability for system reliability. The NDC runs with full plant availability in 2030 have some loss of load in the analysis which would need to be met by diesel or increased on-grid investments not accounted for in the OSeMOSYS modelling. This indicates that improved availability is unlikely to resolve all flexibility issues on its own, and therefore greater investment in storage or sector coupling (which are outside the scope of this study) may be needed to fully optimize the system. Future work could explore this dynamic.

5. Discussion

5.1 Comparisons to Previous Work

Generation mix

The generation mix in the scenarios presented here appear broadly consistent with previous modelling work. The BAU energy mix relies heavily on natural gas with some hydropower. Due to the nature of the scenario most of the results in previous work are broadly similar and show high reliance on gas and hydropower which dominate the existing generation mix (Avila et al., 2017; Roche et al., 2020; Dioha & Kumar, 2020). One deviation of note is the lower diesel generation level in 2030 (59 TWh) than projected by Dioha and Kumar (90 TWh) and Roche (130 TWh). These two studies used higher overall demands than this study and larger demands for off-grid technologies. This likely explains the dominance of diesel in their scenarios as investment in off-grid renewables is limited in the BAU scenario.

The Least Cost mix explored here has high amounts of natural gas with coal entering the mix in 2030 and biomass playing a substantial role from 2040 onwards. Solar PV plays a larger role in the Least Cost scenarios of many of the other studies surveyed (see Dioha & Kumar, 2020 and Avila et al., 2017) . This difference is likely due to the generation cap placed on solar in this study.

The two NDC scenarios presented above were fairly diversified with wind and solar meeting 30% of demand, bolstered by gas, hydro, and nuclear power. Daggash and Mac Dowell's (2021) modelling of Nigeria's first set of NDCs produced a similar generation mix overall – large amounts of gas with some hydro, coal, solar PV, wind, and nuclear. By 2030, their scenarios have no diesel in the generation mix which matches the runs with 2030 improvement, but runs with slower/no improvement do have diesel generation in 2030. Dioha and Kumar's (2020) NDC modelling does not include any wind or nuclear and instead has much more solar throughout the modelling period. The diesel generation in their modelling for 2030 varies from 25–50 TWh. The model run for the UNDC without plant availability improvement explored here sits at the low range of their modelling at 26 TWh coming from diesel and backstops.

Another key finding in the modelling presented in this paper was that Nigeria would be able to meet its 2030 NDC targets without altering its generation mix if plant availability is aggressively improved. Daggash and Mac Dowell (2021) and Dioha and Kumar (2020) came to similar conclusions that NDCs could be met without overhauling the generation mix. This is despite the fact that modelling was based on the initial NDCs and did not appear to incorporate plant availability. Their scenarios can be considered comparable to the scenarios presented here with full plant availability, which also meet the current lower NDCs.

5.2 Feasibility

Taking the importance of increasing plant reliability for reducing emissions, it is important to contextualize the feasibility of both the proposed rates of plant improvement and the costs associated with implementation.

The model runs with improvement to 2030 anticipate that gas plant availability will improve by 7–8% annually, while runs with 2050 improvement have a lower rate of improvement at only 2%. Historic data on plant availability in Nigeria are limited, but a 2011 report does place average gas plant availability at 40%, which is 3% lower than the 2019 availability figures used as the baseline for this study[4] (Amadi, 2015; Nigerian Electricity Regulatory Commission, 2021). This would indicate an average improvement of 0.4% a year over the 8-year period. Since 2011, however, there have been significant changes in the power sector which include privatization of distribution and generation in 2013. This transition has been far from smooth and, after nearly a decade, there are still significant issues with tariff structures in the new market (Soyemi et al., 2021). Privatization likely had a negative impact on plant availability as new management struggled in untested waters.   So, while the 2050 model runs have higher rates of improvement (2%) there is hope that a decade on from privatization that more proactive plant management can help improve reliability in the sector. In this context, the 2% annual improvement feels achievable, while 7–8% – as given in the improvement to 2030 model runs – may be an overambitious target. The modelling above shows that the higher rate of improvement (runs with improvement to 2030) does offer added emissions reductions, but those reductions are minimal over the model period when compared to runs with slower improvement to 2050.

The above modelling does not include any costs for the increased plant maintenance and management needed to make availability improvements. There are limited data on the anticipated costs for improving plant availability in the literature. Given this, the decision was made to not include any added cost for availability improvement. Instead, the cost difference between scenarios with improvement can be used to gauge a ceiling below which availability improvement would make economic sense. If the costs of improvement are below the difference between a run with improvement and a run without, then the cost of the run with improvement accounting will be economic. Runs without improvement are between USD 111 to 190 billion more expensive than runs with improvement, as costs nearly double in BAU and LC runs without improvement. It seems unlikely that gradual availability improvement would double system costs, given that some costs could logically be recouped through increased power generation per unit. In this context, while the exact costs of improved management are murky, it seems that they are likely lower than the costs of continued mismanagement even without accounting for the value of the lost load or the social and environmental costs of generator usage, which would further increase the expense of runs without improvement.

In terms of EE the reductions in demand are broadly in-line with historic EE improvements globally. EE in the European Union increased by an average of 33% across sectors from 1990 to 2016 following the introduction of the appliance labelling standards in 1992 (European Environment Agency, 2019). In this context, the modelled reductions of 20% reduction by 2050 are reasonable, if ambitious.

5.3 NDCs and Policy Implications

In the context of the nation's NDCs, results indicate that Nigeria will need improvement in plant availability/management to meet any commitments. Aggressively improving plant availability would allow the nation to hit its 2030 UNDC target without changing the generation mix. A more gradual, and likely more feasible, improvement pathway would require more aggressive investment in solar PV and some deployment of EE, as demonstrated in the Least Cost run with 2050 improvement.

In the long term, improved availability will also become important for dispatchable generation as the share of variable renewable energy (VRE) is raised over 30%. The low flexibility of runs with reduced availability, even at low levels of VRE, indicate that a system with such low available capacity is unlikely to be able to respond to even quicker and more dramatic changes in net load that are expected at higher VRE penetration. This is particularly important given the announcement that the nation intends to reach net zero in 2060 (Akintunde, 2021).

While the broader global warming implications of generator use are vital, local particulate matter and air quality implications also provide a strong argument for improving Nigeria's energy sector. In the BAU scenario, generator use will increase ten-fold by 2065. The negative health impacts are already apparent with current levels of generator usage and are likely to increase with rising generator usage. There are also significant added costs to homes, businesses, and the economy that come with this continuing reliance. These added costs have significant consequences for sustainable development in the nation and would present significant hurdles in reaching SDG goals 3 (Good Health and Well-being), 7 (Affordable and Clean Energy), and 13 (Climate Action) most directly (UNDESA, 2022).

Given these findings, Nigeria should prioritize better plant maintenance and management practices in policy with the goal of increasing plant and system reliability. This is particularly important in national policy to support the 2021 NDC commitments as long-term decarbonization goals cannot be met without improvements in plant availability. To target this issue, previous work has suggested the introduction of preventative maintenance practices and improved tariff structures which incentivize similar cost-effective operational measures (Oyedepo et al., 2014; Soyemi et al., 2021).

Policies should also support EE as these same long-term reductions in emissions are not possible without efficiency improvements. Current policy in this area lacks action and clear incentive structures. Lessons from other African nations suggest that the government subsidize access to cheaper and more efficient lighting and set clear appliance standards (Soyemi et al., 2021).

[4] Here an average of the SCGT and CCGT availability factors used here (43.5%) is compared to the number used in the 2011 study as they did not indicate the split between CCGT and SCGT plants in the installed capacity.

6. Conclusions

Nigeria struggles with significant reliability issues in its power grid which have spurred the dominance of diesel backup generation in the nation. These reliability issues can be partially traced back to low plant availability and insufficient capacity to meet growing demand. The resulting persistent blackouts and reliance on generation at such a scale has marked impacts on the economic and social development of the nation and presents a considerable barrier in realizing the latest round of NDCs.

While existing modelling explores Nigeria's 2015 NDCs, there is no modelling which yet evaluates the most recent NDCs, or which deliberately explores the dynamic between plant availability, generator usage, and the resulting economic and climate impacts. This study filled that gap through the development of an optimization model in OSeMOSYS supported by a FlexTool flexibility analysis to further validate results and better evaluate the system adequacy. Building on the findings of previous work, the impacts energy efficiency (EE) are also accounted for across scenarios.

Modelling has shown that lack of plant improvement, the consequent supply inadequacy, and reliance on diesel generation present significant barriers towards emissions reduction. Across scenarios, improved plant availability was found to lower emissions, system costs, and loss of load in the flexibility modelling. Increasing plant availability by 2% each year until 2050, the more modest and achievable of the two improvement pathways, produces average emissions and cost savings of 45% across scenarios.

These findings underscore the importance of improvements in plant and grid reliability for meeting emissions and development goals. They suggest that Nigeria should prioritize preventative maintenance and performance-reflective tariff structures as well as concrete energy efficiency standards/incentives in policies to support the 2021 NDCs.

Declarations

CRediT author statement:

Sarah Golobish (1): Conceptualization, Methodology, Writing - Original Draft, Writing - Review & Editing

Rudolf Yeganyan (1,2): Writing - Review & Editing

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Acknowledgements:

"This material has been produced under the Climate Compatible Growth (CCG) programme, which brings together leading research organisations and is led out of the STEER centre, Loughborough University. CCG is funded by FCDO from the UK government. However, the views expressed herein do not necessarily reflect the UK government's official

policies. This work was developed with the Energy Transition Council (ETC), which assisted in identifying needed research areas and connected to relevant stakeholders for a discussion on essential aspects of research. This paper was edited by Simon Patterson (CCG, Loughborough University).”

U4RIA Compliance:

“This work follows the U4RIA guidelines [Source] which provide a set of high-level goals relating to conducting energy system analyses in countries. This paper was carried out involving stakeholders in the development of models, assumptions, scenarios and results (Ubuntu / Community). The authors ensure that all data, source code and results can be easily found, accessed, downloaded and viewed (retrievability), licensed for reuse (reusability), and that the modelling process can be repeated in an automatic way (repeatability). The authors provide complete metadata for reconstructing the modelling process (reconstructability), ensuring the transfer of data, assumptions and results to other projects, analyses and models (interoperability), and facilitating peer-review through transparency (auditability).”

Declaration of competing interest:

“The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.”

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Figures

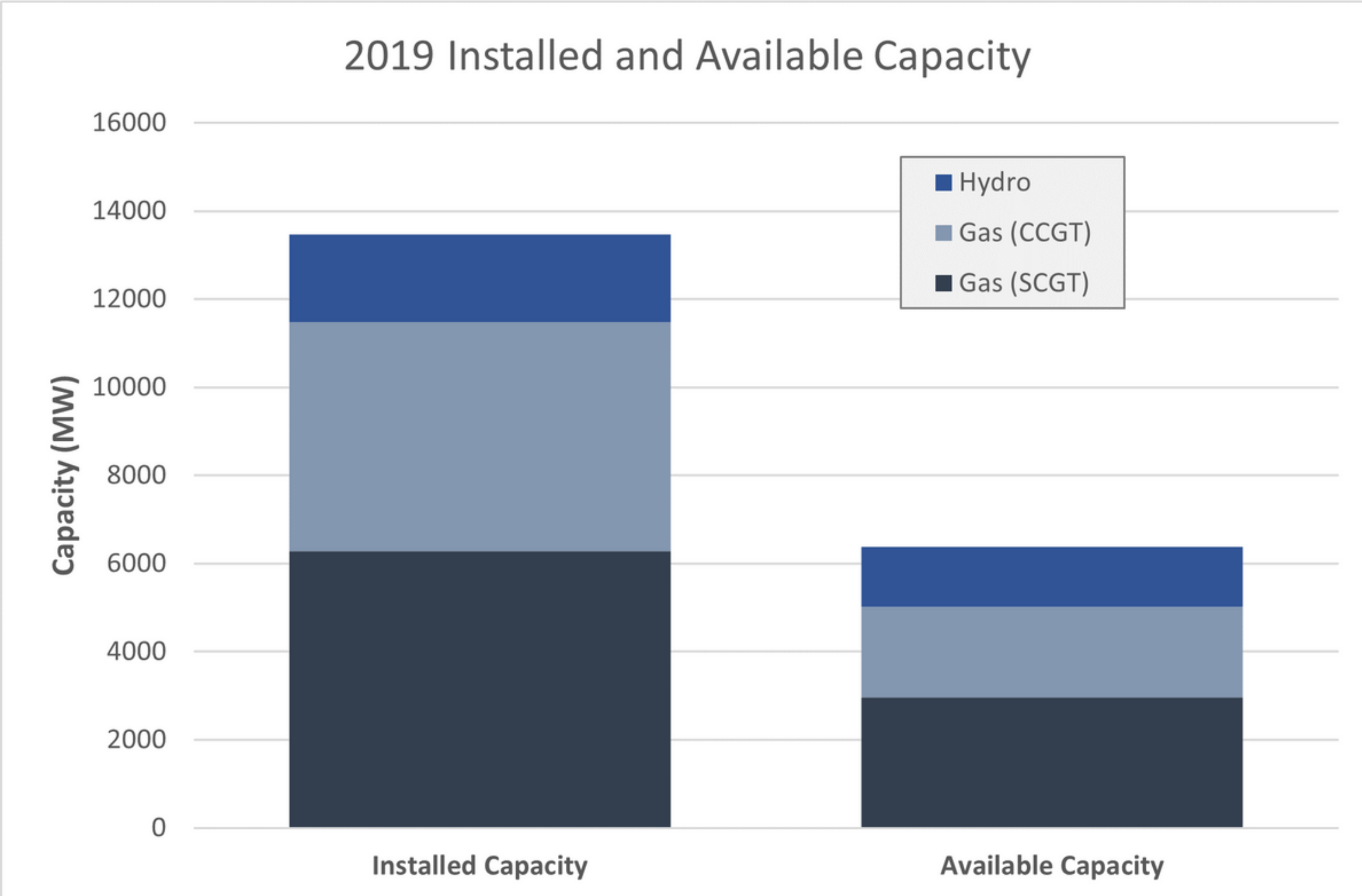

Figure 1

2019 Installed and available on-grid capacity in Nigeria.

Installed Capacity: NERC (2018), Available Capacity: NERC (2021). SCGT = Single cycle gas turbine; CCGT = Combined cycle gas turbine.

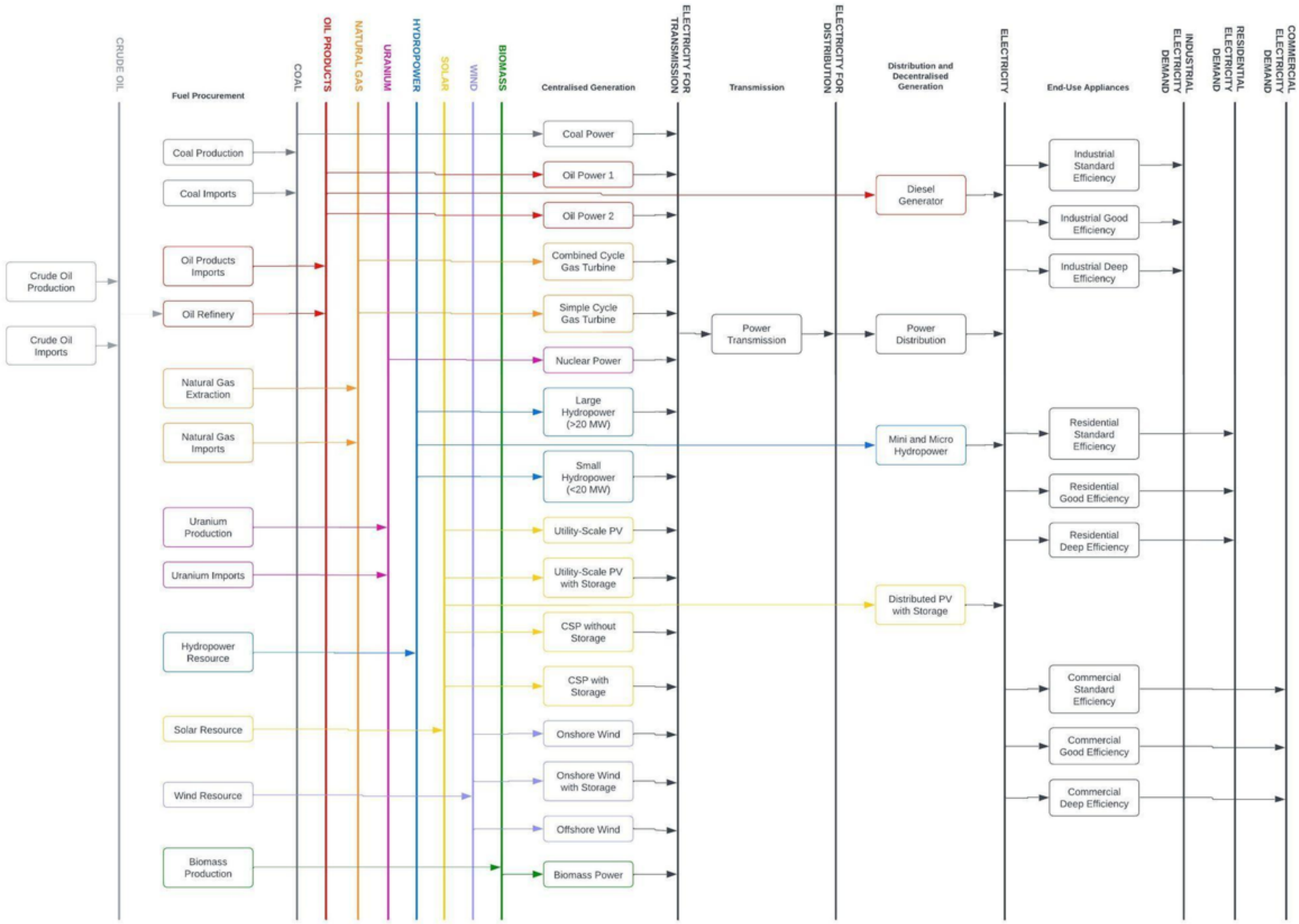

Figure 2

Reference energy system for Nigeria.

Adapted from Allington et al. (2021). CSP = Concentrating Solar Power

Figure 3

Generation in the Business-as-Usual scenario

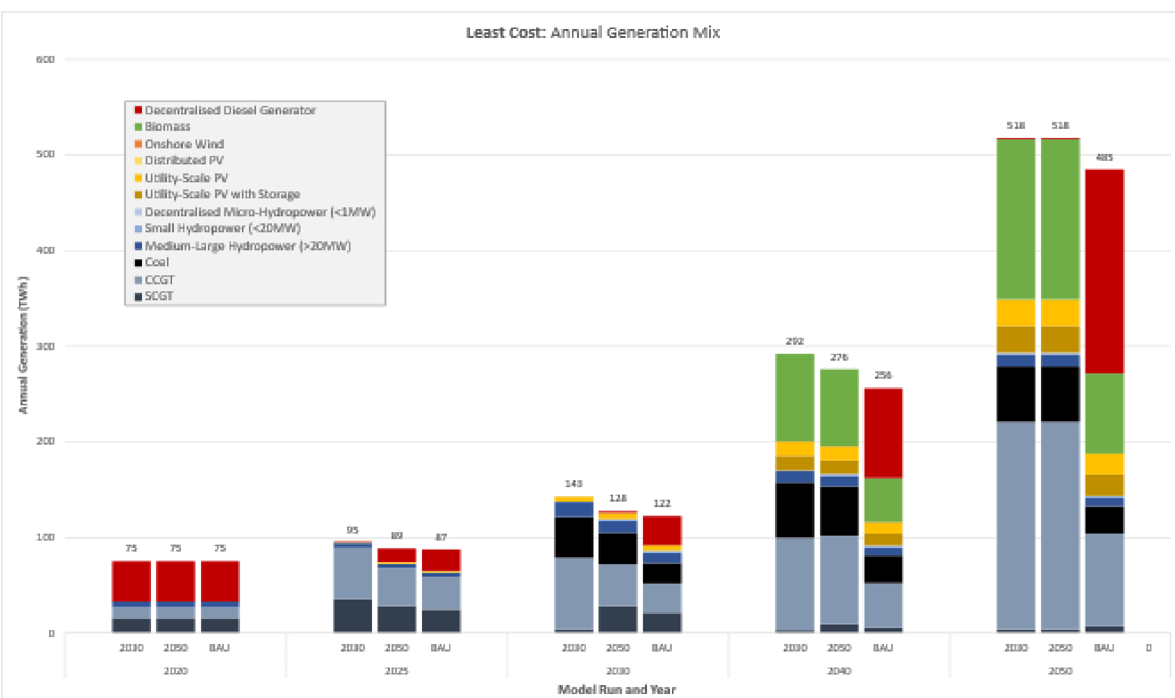

Figure 4

Generation in the Least Cost scenario.

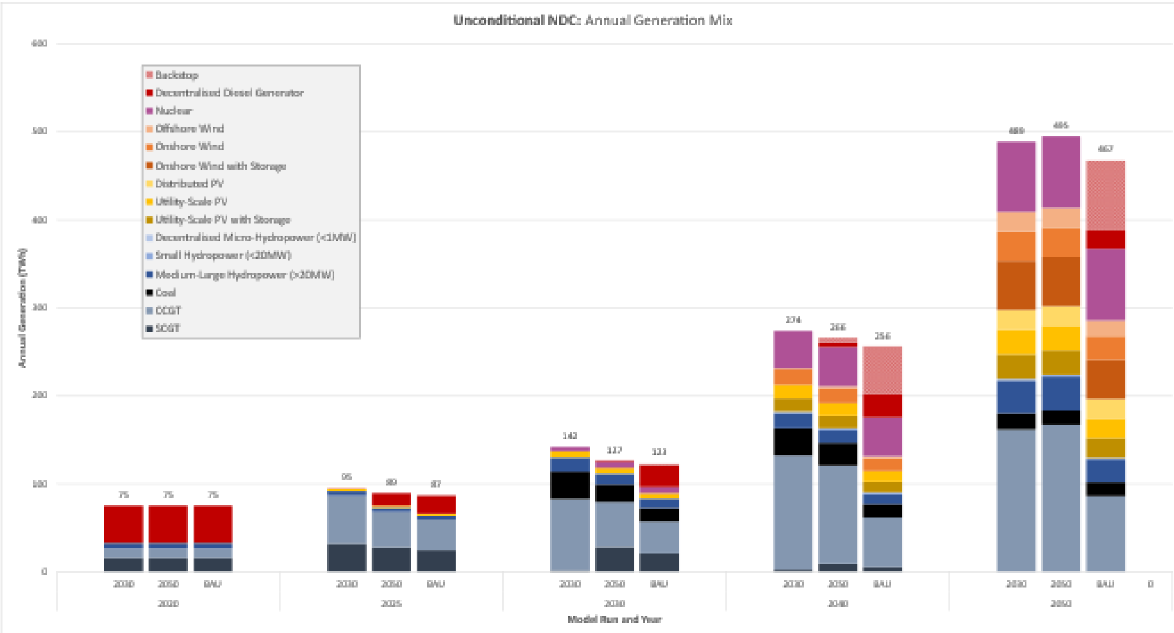

Figure 5

Generation in the UNDC scenario.

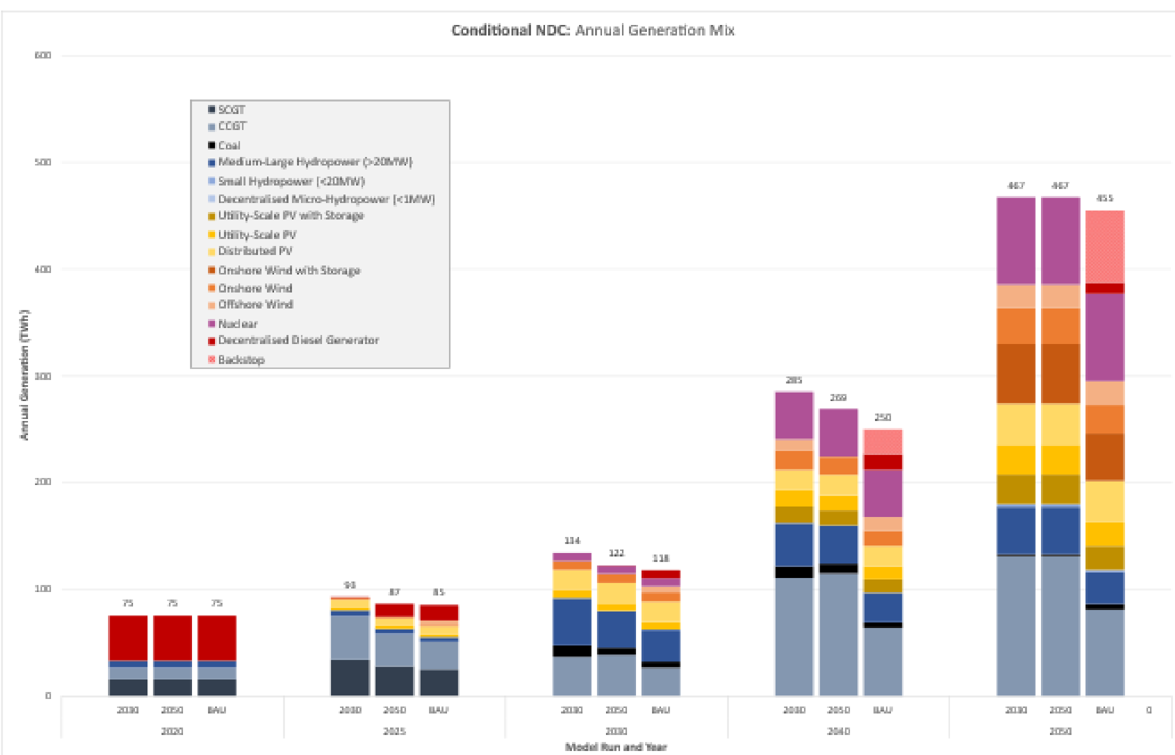

Figure 6

Generation in the CNDC scenario.

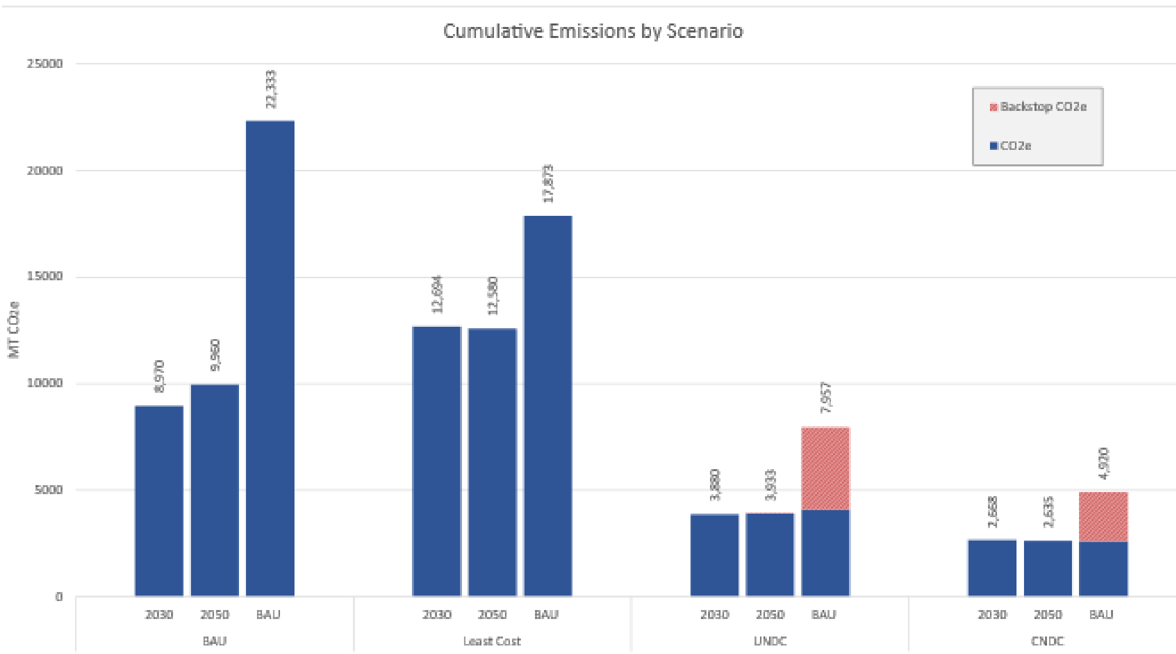

Figure 7

Cumulative emissions by scenario from 2015–2065.

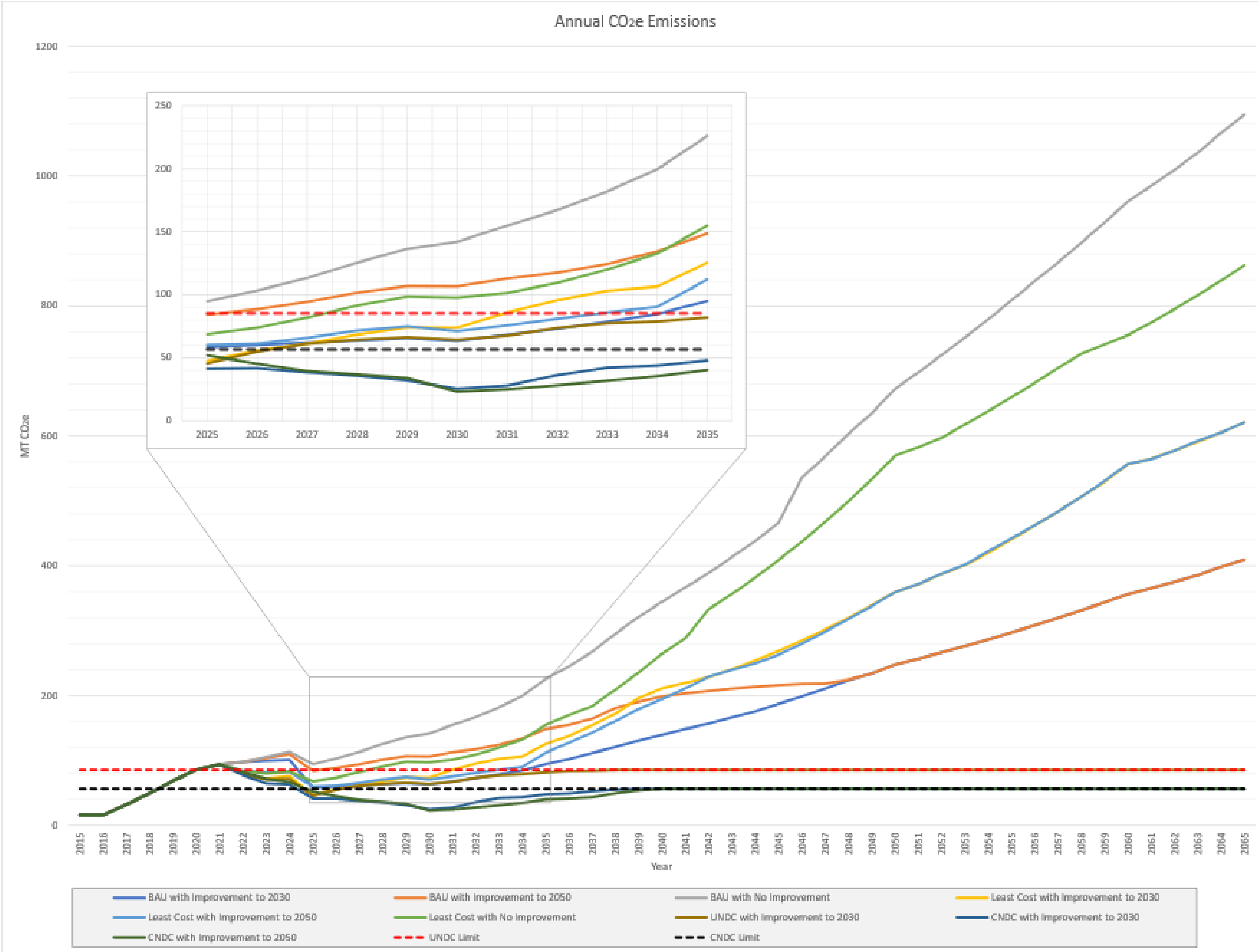

Figure 8

Annual emissions by model run from 2015-2065.

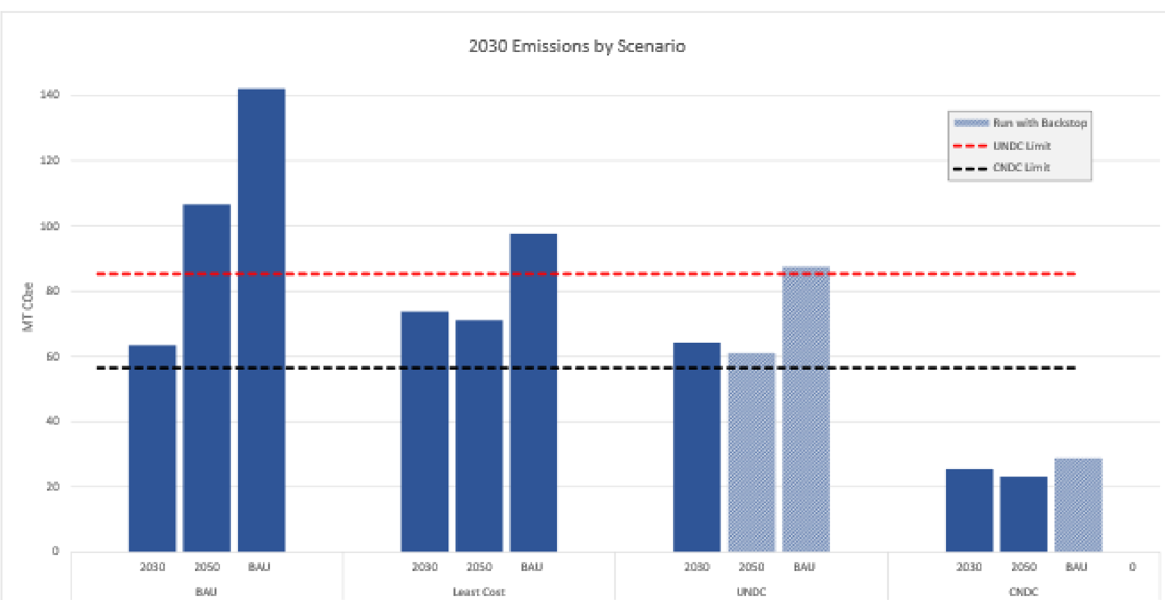

Figure 9

2030 emissions by scenario.

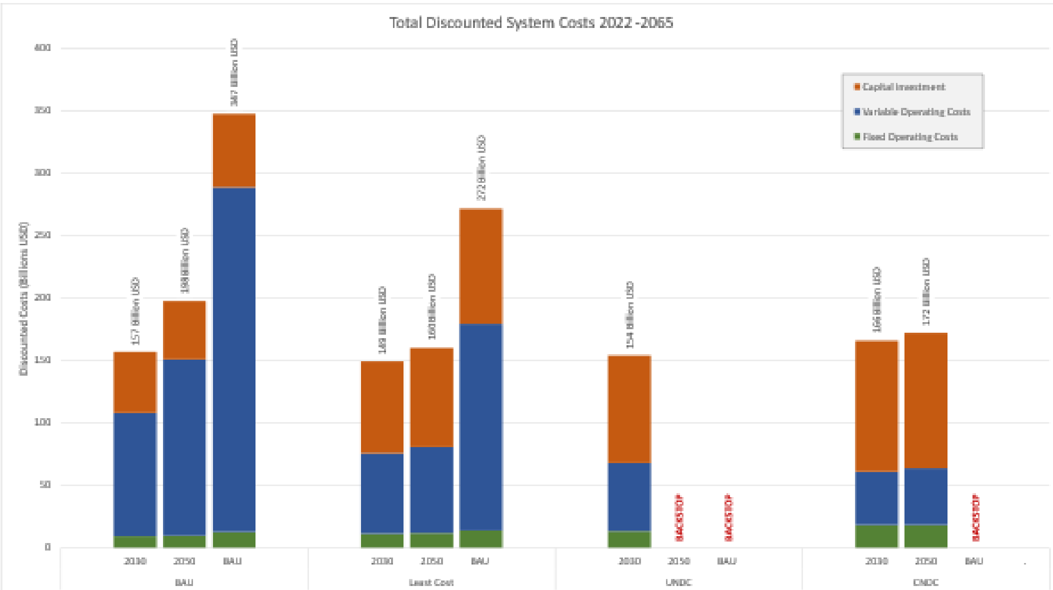

Figure 10

Total discounted system costs from 2022–2065 by scenario.

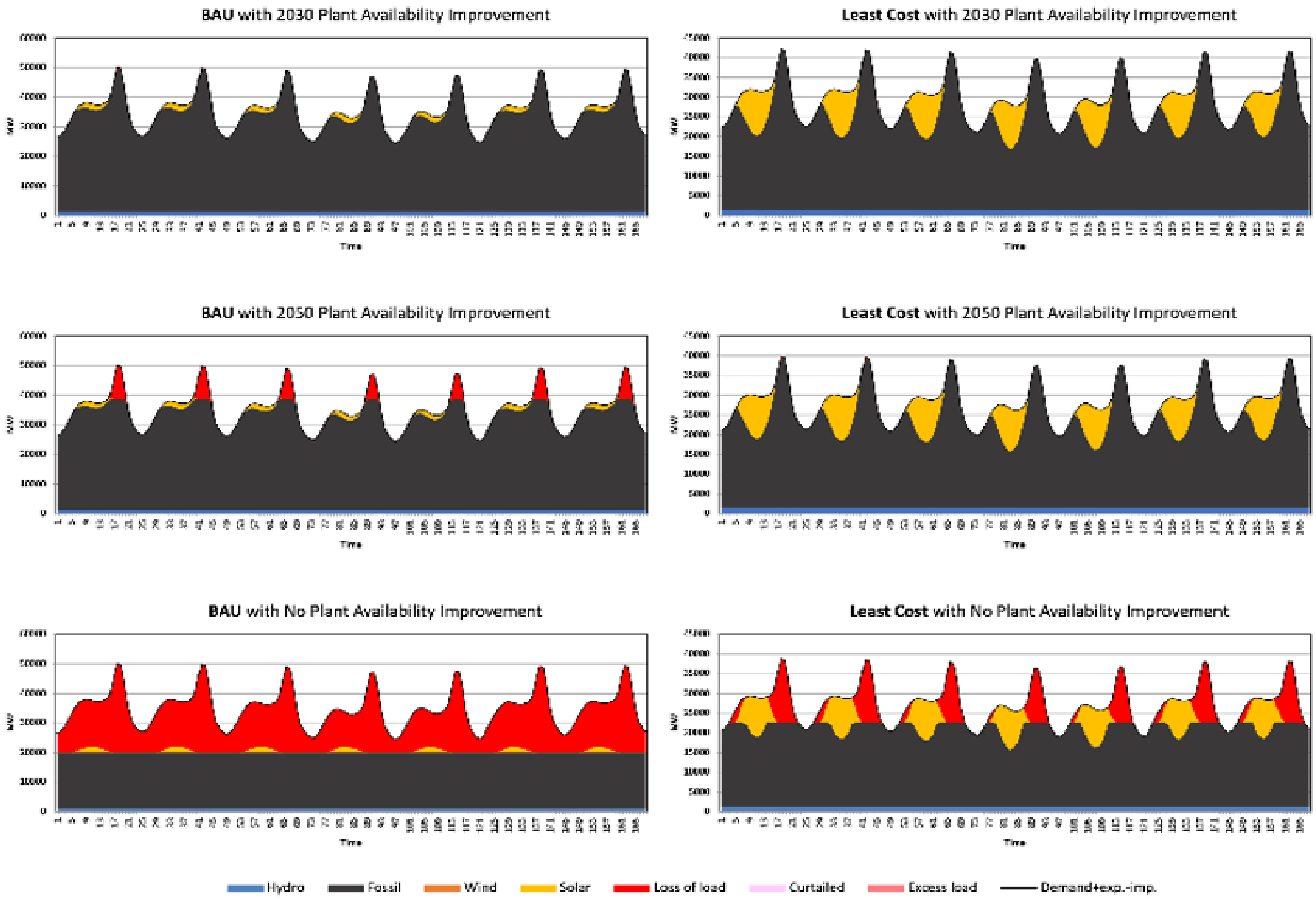

Figure 11

Load curves for BAU and Least Cost model runs

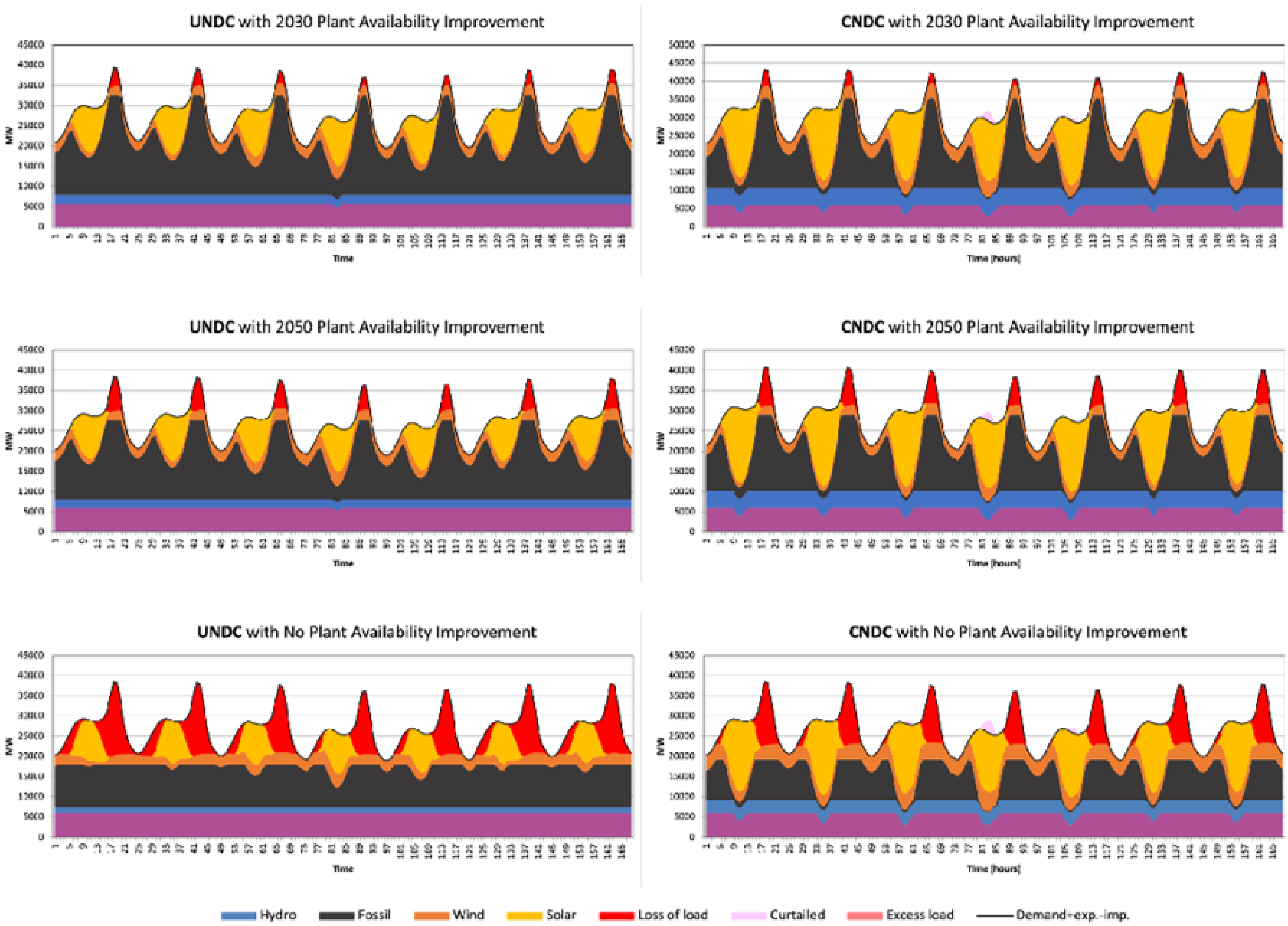

Figure 12

Load curves for UNDC and CNDC model runs.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- AppendixA.docx
- AppendixB.docx
- AppendixC.docx