# Comparative Analysis of Residential Solar Farm with Energy Storage between the USA and Nigeria

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***Abstract*—Unlike the United States, Nigeria's installed overall electricity capacity is 12.8 GW, while the operational capacity is estimated to be 3.9 GW which is well below the current demand of 98 GW. This results in a consumer power demand shortfall of 94.1 GW across the country. As a result of this wide gap between demand and generation, only about 45% of Nigeria's citizens have access to electricity. In this paper, a comparative feasibility analysis of the utilization of a photovoltaic system with energy storage for residential application is presented. The comparative analysis is conducted to compare the feasibility of using a solar Farm with an energy storage system between the US and Nigeria. This analysis is carried out using a model developed by IREQ Hydro-Quebec Research Institute. The results are shown in phasor form to analyze the energy stored, solar intensity, and also enable the community in making informed decisions regarding reducing grid dependency.**

***Index Terms*—energy storage systems, power system operators, photo-voltaic, renewable energy technology, Solar System**

## I. Introduction

Nigeria is located in Africa, and has the continent's largest population count at close to 200 million people. Nigeria's Energy Policy report released in 2003 shows that this population is disconnected from the grid system roughly 60% of the time [1]. Nigeria's power grid is primarily powered by gas, hydro-power, and oil as indicated in Table I [2].

TABLE I
Nigeria Electricity Structure

| Source | % Contribution |
|---|---|
| Gas | 37.0 |
| Hydroelectric | 35.6 |
| Oil | 27.0 |
| Coal | 0.4 |
| Photovoltaic | 0.0 |

Due to the absence of a constant power supply, individuals and companies often supplement the power available from the grid using personally owned generators. Nearly everyone who can afford a gas-powered generator owns one. Today, reliable and portable energy storage devices are gaining popularity. Large solar farms are now becoming more common in many rural settings across the world. Access to constant electricity is transitioning from a technical issue into a financial issue.

Unlike in the US, Nigeria is facing serious electricity deficiency. The grid system is unstable and exposed to sabotage, the shortage is due to a mix of financial, structural, and socio-political issues [18]. In this work, we aim to analyze Nigeria's power issue and provide recommendation and potential solutions. The remainder of this work is organized as follows. The complexity, versatility, and capability of energy storage currently in use are reviewed in Section II. Section III analyzes the model employed for residential energy storage in the southwest region of the US, and then compares it to a location in Nigeria to determine its feasibility. Section V discusses the simulation model and its results as well as PV performance ratio, economic importance and future implementation.

## II. Literature Review

Nigeria energy crisis has become an almost inescapable phenomenon which has generated numerous research studies with a different point of views, from power sector crisis [2], power infrastructure [22], renewable energy investment [20], to renewable energy integration [21]. It has become evident that the people living in this country lack access to constant and reliable source of electricity [23].

Onochie et al. attempted to highlight the large existing deficit in the electricity generation by the country's power providers and the demand from consumers. They concluded that consumers supplement the grid-provided power with other means of power generation. This is why many reporters in Nigeria's power sector have utilized the term "generator economy" since almost everyone who can afford a gas power generator owns one [2].

Ebele et al. explained why Nigeria faces a number of developmental challenges including the risk of losing potential investors for power infrastructural development. They recommended that the Nigerian government and Power System Operators (PSOs) should all make concerted efforts towards growing and developing the power infrastructure. Their recommendation was based on their analysis of a study which emphasized that the infrastructure deficits requires about 8.1 trillion Naira (about $22.4 million) in investments [22].

Udochukwu et al. findings indicated that there is no interest in investing in adding renewable energy in Nigeria. The reasoning behind this is the fact there is currently a high dependence on conventional resources for energy generation. A Renewable Energy Master Plan (REMP) was further presented in their study, which would help emphasize Nigeria's

commitments to achieving a developmental project that includes all major renewable energy resources. The successful execution of this project will result in the installation of 2.9 GW of major renewable energy resources from wind, solar, mini-hydro, and biomass by the year 2025. This expansion will be roughly equivalent to the current operational grid capacity in the Country [20].

Matthew et al. findings indicated that Nigeria's electric power plants mainly use fossil fuels and have a large carbon footprint, which contributes to climate change. It was concluded that sustainable power generation from renewable energy sources in Nigeria is achievable through careful consideration of the source and storage technology employed [21]. However, the present government has no definite strategy to untangle the mess of energy privatization because of the dubious associated performance agreements signed in 2013, which was based on political patronage [19]. Regardless, understanding how energy storage has modernized other countries' power grids could motivate Nigeria to act [6].

## III. Energy Storage and Technical Challenges

Power system operators are required to match customer demand. The grids performance is regulated by the law of the nation in which they are based. Generation and distribution must satisfy customer demand, which fluctuates uncontrollably as defined in the challenges below [5].

### A. Matching the Supply to the Demand

During the disturbance, such as a short-circuit, failure of a generator, or large drop in load, adapting the electricity supply to match the demand is always a challenge which defines performance. For stability to be achieved, the utilization of rotating inertia is important. This is especially true when integrating renewable power sources which have little to no inertia contribution to the system making balancing more difficult. Thus, new solutions for fuel based backup generation systems are required in order to mitigate the risk of frequent blackouts. To achieve this, two unique requirements must be considered by the electric power system [6], 1) Maintaining a close real-time balance between generation and load, 2) Adjusting generation (or load) to control power flows via each transmission point.

### B. Dispatchability

Generation sources that can be called upon at any time to generate electricity are referred to as dispatchable sources. A method by which PSOs make a decision related to the output capacity of their generating plants which can be increased to full generation quickly when power shortages arise. The following parameters are key and required to technically dispatch [7]:

- Lead-in Time, also known as Response Time: is a the time it takes the power supply to match the power demand whenever a mismatch occurs.
- Available Power: is the minimum continuous output power which the generator can deliver.
- Duration: is the minimum period during which the specified power delivery can be sustained.
- Time Range: is the time for which the power generated will be available and guaranteed.
- Location: The transmission loss is dependent on the distance which can be larger for longer distances.
- Pricing: is dependent on the other listed factors.

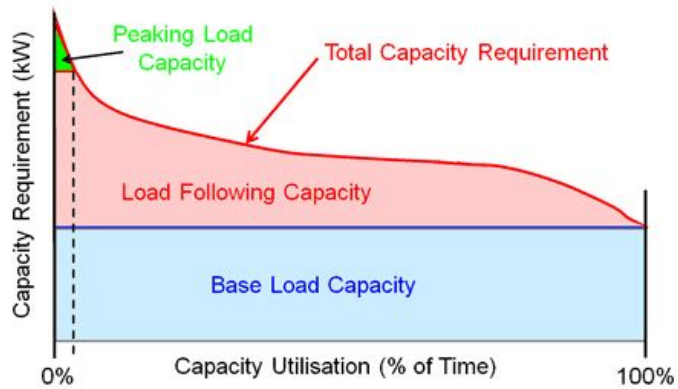


Fig. 1. Load Duration Curve [6]

Figure 1 shows the base load, load following, and peak load capacities of an electrical supply system over a 24 hour period represented as percentage. The base load is continuous and is matched using the most efficient plants operating at their optimum capacity [6]. This figure also illustrates the load profile in order to better understand the type of generating capacity required to meet the demand and its expected utilization. Dispatchability is important and can be characterized as follows:

#### *(i) Slow/Non-Dispatchable Assets*

Base load capacity is technically designed to run continuously and have a long lead-in time. It comprises of very high efficient thermal base-load generation plants, which is also known as slow or non-dispatchable assets, such as nuclear generation.

#### *(ii) Irregular/Non-Dispatchable Assets*

The main components of major renewable energy resources such as river-side hydraulic plants, solar farms, and wind farms give rise to a level of unpredictability in the energy generation. This is why they are classified as non-dispatchable since they can't be depended on to fulfill required demand when requested to do so [6].

#### *(iii) Rapid/Dispatchable Assets*

Adaptable back-up generators, a common example of rapid or dispatchable assets, have a high factor rated capacity and are used to manage sudden fluctuations in demand thereby ensuring that power demand is consistently met. Batteries are one of the fastest responding assets having lead-in times of less than one second. This feature makes it possible for batteries to be called upon within seconds when needed [6].

### C. Transmission and Distribution

The Transmission and Distribution (T&D) Network is the most significant part of the electricity grid since it makes it possible for energy to be delivered to consumers. The networking involves two distinguishable yet connected systems as stated below:

- Across thousands of miles, a high-voltage transmission system is designed to transmit electric power from generation plants on the national grid. The framework is arranged such that power has various paths to follow from the generation to the appropriate distribution substation.
- The main distribution system is structured to control millions of miles of lower-voltage electrical conductors using the power grid at the distribution substations. The power distribution is realized to reach about a million customers [6].

### D. Balancing Electricity Supply in Case of Calamities

The economy of any country is largely centered on a reliable and constant supply of affordable electricity. One challenge is to ensure that the supply system is constant and cheap [1]. Analysis of what occurs in the failure of power plants is a good example. Lets say we have ten generating power plants needed to supply electricity with the same power capacity. If each of these ten plants has a nominal capacity of 5 GW, then all of the plants operating at 90% of their capacity will meet 10% of particular primary control reserves. This will be sufficient in theory to compensate if any one of the ten power plants fails as shown in Figure 2. The electricity capacity demand that all the generating power plants supply is almost equivalent to 90% of 10*5 GW which equals to 45 GW.

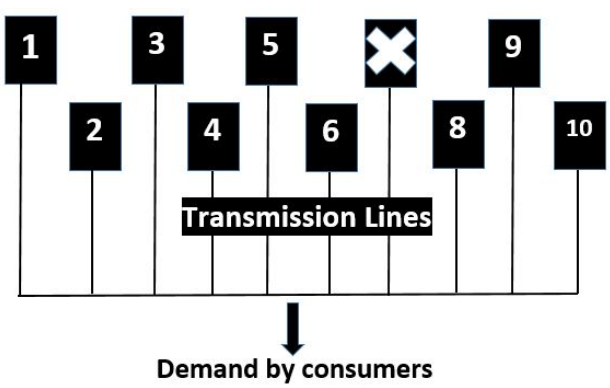


Fig. 2. Ten generating power plants [1]

As indicated in Figure 2, assuming that the seventh plant unexpectedly stops and the operating system is now short of 4.5 GW in supply. The remaining 9 power plants cannot instantaneously increase the power output of their machines to the compensate for the shortage. The generating power plants need some time to respond to the newly desired output value so as to fulfill the total system demand [7].

### E. Consequences of Mismatched Supply and Demand

Assuming there is no energy storage or dispatchable sources, electricity would then only be produced upon request. Consequentially, it would impose a huge risk on the robustness of grid that is designed to serve millions of consumers. This will result in potential fluctuation in voltages at the consumers' end which could damage electronics, installations or event result in intermittent blackouts [6].

### F. Technology of Storage

Renewable energy has a low to marginal cost when operating within the transmission and operating constraints. However, photovoltaic and wind farms are not practically accessible without employing storage systems consisting of large numbers of batteries [6].

TABLE II
ENERGY STORAGE SYSTEMS APPLICATIONS AND BENEFITS

| ESS Opportunity | Applications | Benefits |
|---|---|---|
| Improve Efficiency | Improve load factor | Cost Reduction |
| System Balancing | Matching S/D | Cost Reduction |
| Stabilize Prices | Reduce Prices | Customer Service |
| Manage Voltage Limits | Grid voltage support | Power Quality |
| Renewable Integration | Emergency backup | Enhancement |
| Ancillary Services | System balancing | Power Quality |

Table II summaries the energy storage systems (ESS) opportunities, applications, and benefits. The benefits of ESS can be numerous and the overall purpose is to deliver fundamental improvements to the way electricity is produced and transmitted to consumers.

## IV. Comparison Analysis of Solar Potential

Global concerns for clean air, environment pollution, and global warming have spawned the rapid development of alternative energy such as solar and wind power. Since 2008, power installations have increased rapidly from 1.2 GW to about 30 GW in the United States. This is sufficient to accommodate more than 6.2 million average American homes [7]. To analyze the potential of solar energy in this study, a comparative analysis is conducted using the following two case studies:

### A. Case 1: United States of America

Case Study 1 is the feasibility analysis of installing a residential energy storage system in a developed rural setting in the southeast region of the US specifically in the State of Georgia. The operating system is primarily connected to a 600 Volts community electrical system near the Savannah Airport field. Based on the TMY3 data, given load profile, and the output of the solar farm, the capacity of the energy stored is estimated in phasor mode for a full year. Figure 3 illustrates the solar irradiance in the US indicating that the southeast region of the US has good potential.

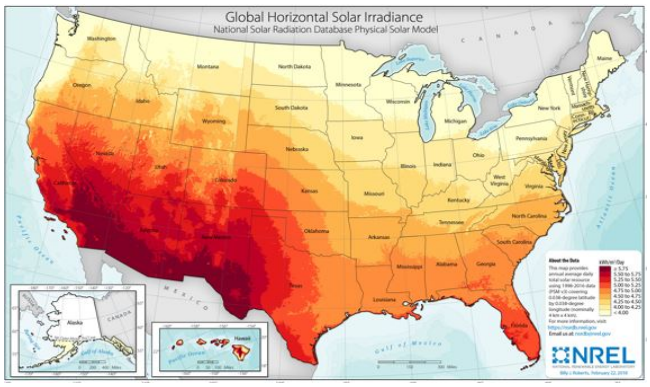


Fig. 3. USA Solar Irradiance Map (Source: NREL)

### B. Case 2: Nigeria

Case Study 2 also analyzes the output in phasor mode connected to a sample grid in an under-developed rural area in Nigeria. The northeast part of the country has abundant solar potential, with enough distributed solar radiation averaging at about 19.8 $MJm^2$/day with solid sunshine hours estimated at 6h-7h/day as illustrated in Figure 4. The concentrated solar power and photovoltaic generation potential can be estimated at 427 GW [11]. The northeastern and western zones in Nigeria offers a highly significant solar energy potential which could be leveraged for the generation of electricity using solar energy.

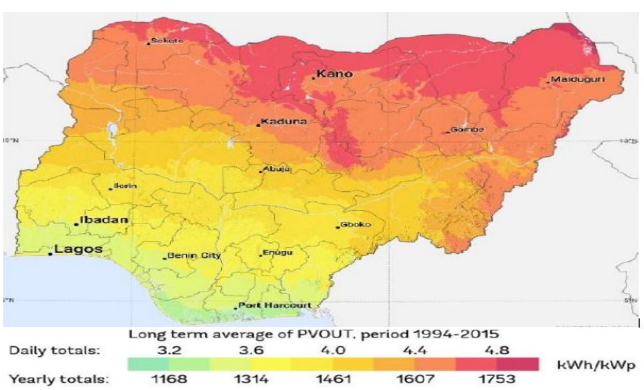


Fig. 4. Nigeria Solar Irradiance Map (Source: NREL)

In this comparative analysis, outputs were obtained using an Energy Storage System Model developed by the IREQ Hydro-Quebec by using public solar data (TMY3 files) and Solar details extracted from open online sources under NASA Surface meteorology and Solar Energy (NASA-SSE) [8]. TMY3 files are online data files obtained from the National Solar Radiation Data Base (NSRDB) archives. The hour-by-hour values of solar radiation of a 1-year period are used in this study. The grid power was simply modeled using the power generated using PV and the power stored in the ESS as indicated in Eq. 1.

$$P_G = P_F + P_B \tag{1}$$

Where $P_G$ is the grid power, $P_F$ is the power generated from Solar farm, and $P_B$ is the total energy stored within the batteries [8].

## V. Simulation and Results

Matlab simPowerSystems is employed to simulate the electrical circuits and control system of a Residential ESS (RESS) which is connected to the power grid through an inverter often using batteries or super-capacitors for energy storage as shown in Figure 5 [8].

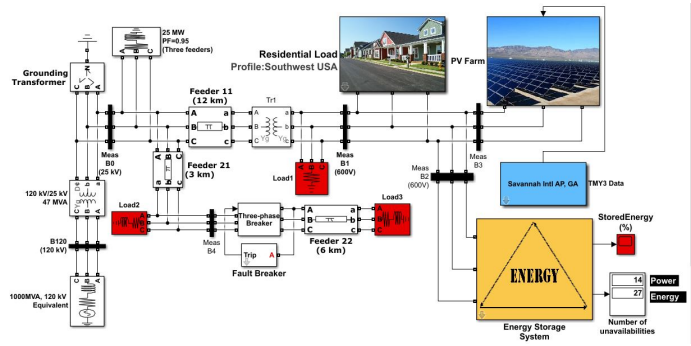


Fig. 5. Residential Energy Storage System (RESS) Model [8]

The Model can be split into 4 major components; First is the Electrical Distribution system, then the Dynamic Load model representing a residential load. The Typical Meteorological Year (TMY) Data block feeding power signal to the PV Farm model and finally the Energy Storage System (ESS) Model as shown in Figure 5 [8].

The Electrical Grid represents a typical North American Utility Distribution System, it consists of 120KV transmission system equivalent supplying a 25KV distribution substation. Several feeders are connected to the 25KV BUS on the substation, one of them supply the power to a community that owns the PV farm and an Energy storage system. The Second part of the model is the dynamic load, it implements a 3 phase 3 wire dynamic load based on the load profile. The profiles are daily load profiles specify on an hourly basis. The third part is the TMY Data System, it converts Solar Irradiance data to power. This power signal is from the simpower system PV Farm that converts power signal to current. The last part of the Model is the ESS, it contains the following components: A control system, an unavailability monitor, a stored energy calculator, and a step-up transformer.

Figures 6 and 7 illustrate the estimated PV cell temperature over one year period for Savannah and Sokoto respectively. The temperature coefficient plays a critical role in every solar panel performance. Almost every solar panel have a temperature coefficient ranging between $-0.2\%°C$ to $-0.5\%°C$. Thus, the closer the temperature coefficient is to zero, the better it will perform [17].

Additionally, the solar irradiance for both Savannah and Sokoto is illustrated in Figures 8 and 9. This indicates the potential solar power that can be used to generate electricity at each location. Irradiance is slightly changing throughout the

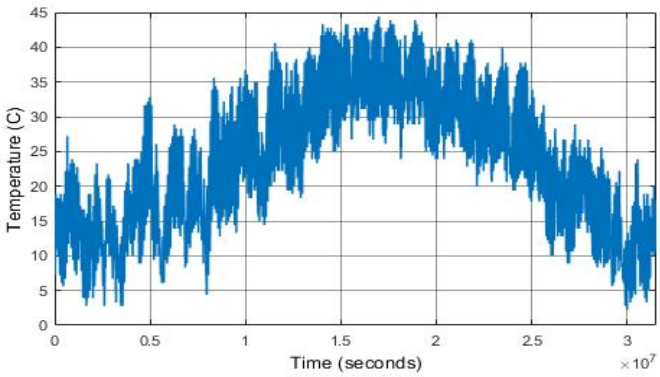


Fig. 6. Estimated PV Cell Temperature - Savannah, USA

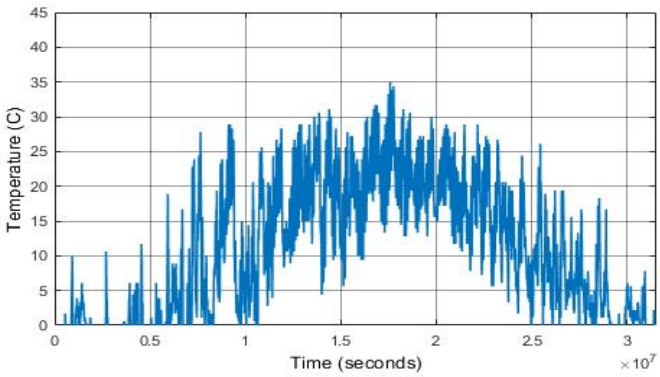


Fig. 7. Estimated PV Cell Temperature - Sokoto, Nigeria

year and dependent on the natures of the season. It also varies throughout the day as well and depends on the position of the sun in the sky, and the condition of the day's weather. Above atmospheric heights, the energy density of solar radiation is estimated to be around 1,368 $W/m^2$. However, the energy density is lower at the earth's surface and estimated at 1,000 $W/m^2$ for a surface perpendicular to the Sun rays at sea level on a clear day.

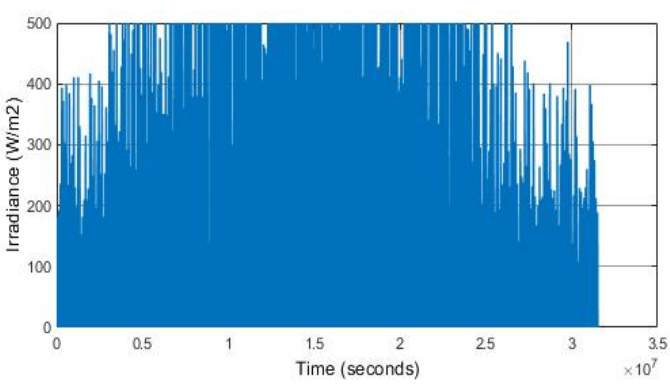


Fig. 8. Estimated Solar Irradiance - Savannah, USA

The location and type of sites chosen for the case studies is also can impact its outcome. Hence, the installation in both

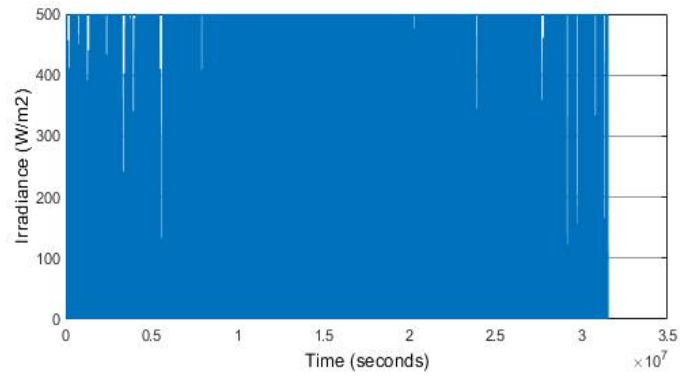


Fig. 9. Estimated Solar Irradiance - Sokoto, Nigeria

case studies was in an open airport field. A solar cell can get as hot as 65°C, causing the panel to become less efficient and effective. A straightforward scenario was chosen to estimate the power and capacity of the Model used in this analysis. The parameters for the simulation model for both case studies were chosen to be similar as indicated in Table III.

TABLE III
MODEL PARAMETERS FOR BOTH LOCATIONS

| **Model of the ESS** | **Details** |
|---|---|
| Rated Power in kW | 275 |
| Rated Capacity in kWh | 1000 |
| Initial stored energy | 90% |
| System efficiency | 96% |
| Max power from Grid (kW) | 1000 |
| Regulation integral Gain | 1000 |
| Max Charge (kW) @night time | 150 |
| **Load Profile** | **Solar farm** |
| Nominal V(L-L) = 600 | Global H-Irradiance |
| Nominal Load = 1500 KVA | PV Total Area = 3000$m^2$ |
| Power factor = 0.95 | System efficiency = 90% |

As a result of the simulation model, the grid power, energy storage, residential load, and PV-generated power for both Savannah, GA, US and Sokoto, Nigeria are shown in Figures 10 and 11 respectively.

### A. Solar Cell Performance Ratio

A solar cell performance ratio is the ratio between the main yield otherwise know as actual yield (i.e. the average annual electricity that is produced and delivered) and the target or required yield. It is independent of the irradiance and therefore, used to compare systems [13].

Since deterioration helps to identify causes of yield losses, it is essential to take the measurement of performance ratio throughout the operation of the system. Eq. 2, further explains the performance ratio a Solar cell [12].

$$PR = \frac{Actual\ Yield_{AC}}{Target\ Yield_{DC}} = \frac{E}{hA\eta_{nom}} = \eta_{pre}\eta_{rel}\eta_{sys} \qquad (2)$$

### B. Energy Target Output

The capacity of energy E, needed or targeted to be delivered by an RESS is estimated using Eq. 3 below [13]:

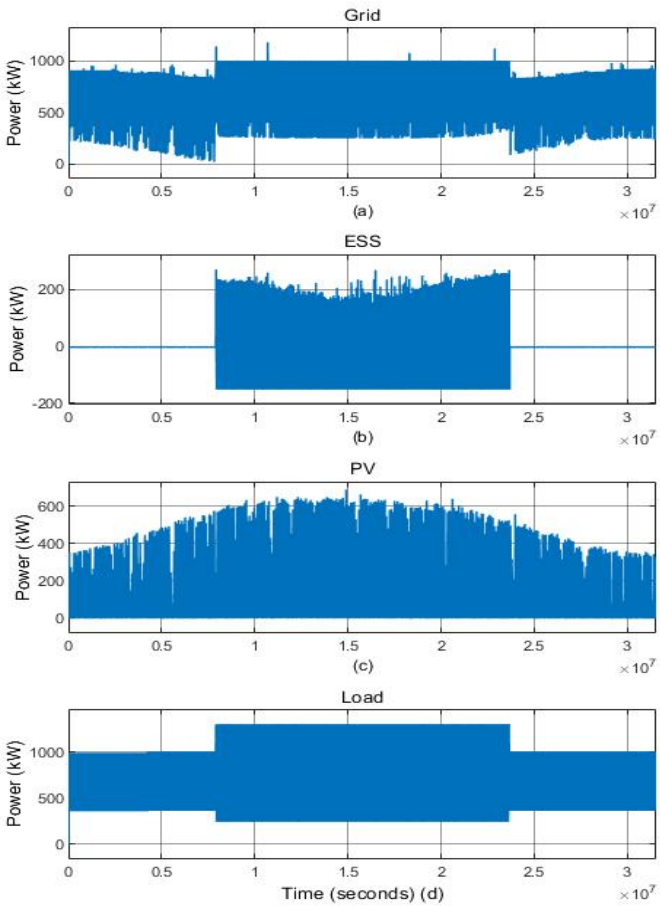


Fig. 10. (a) Estimated Power of Grid (b) ESS Capacity (c) PV Power (d) Estimated Load - (Savannah, USA)

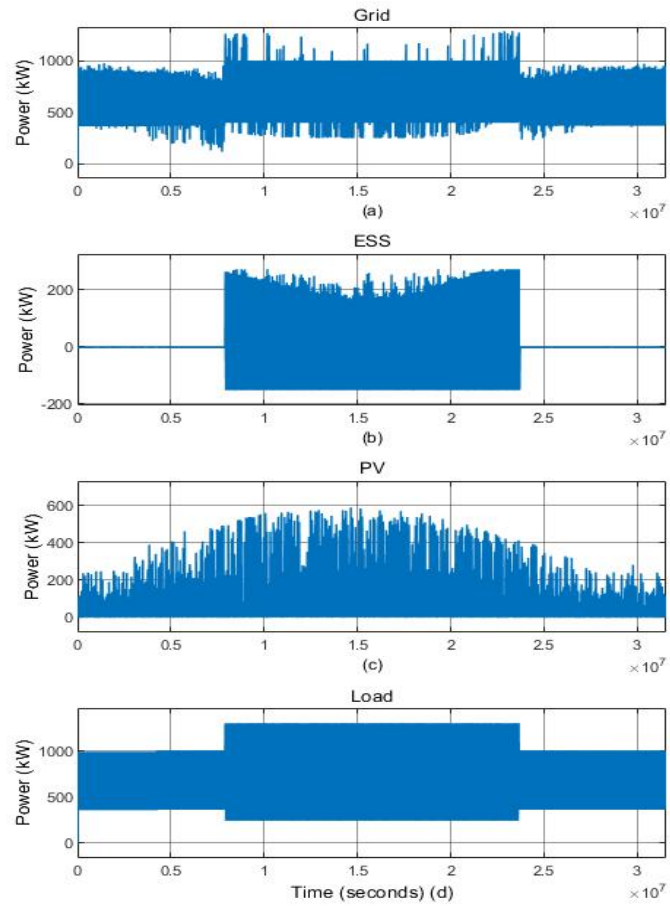


Fig. 11. (a) Estimated Power of Grid (b) ESS Capacity (c) PV Power (d) Estimated Load - (Sokoto, Nigeria)

$$\frac{E}{A} = h\eta_{pre}\eta_{rel}\eta_{sys}\eta_{nom} = PRh\eta_{nom} \tag{3}$$

Where $\eta_{pre}$ is the pre-conversion efficiency, $\eta_{sys}$ is the system efficiency, $\eta_{rel}$ is the relative module efficiency, $\eta_{nom}$ is the nominal module efficiency and $h$ is the yearly sum of global irradiance $[kWh/m^2]$ [13].

### C. Energy Per Rated Power

In many conditions, the amount of energy yield is normally expressed in terms of the peak power of the module, this power is not dependent on the area of the module and it is rated as (with $H_0$= 1,000 W/$m^2$)[13].

$$\left(\frac{E}{P_{peak}}\right) = \frac{h}{H_0}\eta_{pre}\eta_{rel}\eta_{sys} = \left(\frac{E}{A}\right)\frac{1}{H_0\eta_{nom}} = PR\frac{h}{H_0} \tag{4}$$

Eq. 4 defines the energy per rated power and states that the peak power in the equation is the module's peak power, not the systems' installed rated capacity, which is $P_{sys} = P_{module}\eta_{sys}$ [13].

## VI. Future Implementation

It has been declared by United Nations General Assembly unanimously that for the decade 2014-2024, all nations must transform to Sustainable Energy for All. With the integration of robust solar systems into the national grid, Nigeria is capable of simultaneously achieving production and distribution of a minimum of 8.0 GW in 18 months. The limit capacity of the old and the 10 new power stations is at least 8.0 GW [13]. The power generation, however, hits 5.09 GW, the highest achieved in April 2018.

To successfully adopt the resolution, Nigeria can immediately begin the implementation of the following [14]:

1) Developed countries normally decentralize control of the energy sector to ease the management. The sources, funding, generation, transmission & distribution are also decentralizing. The energy sector in Nigeria is however centrally regulated and has made the situation for corrupt practices to thrive [18].
2) The power system setup should be addressed as a state of emergency. This is to empower, strengthen and expand the grid [18].
3) Nigeria should take advantage of global partnerships with major NGOs at both local and international levels.

4) The Federal Government could mandate the Power Holding Company of Nigeria (PHCN) to promote the use of renewable energy in the power sector and ensure energy efficiency practices.
5) Multinationals and Private sectors should be supported in the form of incentives and subsidized investments by the Nigeria Government to embark on energy efficient projects through the introduction of renewable energy solutions.
6) Research and Development centers including technology development institutions, like Universities and Polytechnics, should be funded and strengthened to assist explore increased renewable energy utilization.
7) With the view to developing energy service companies, and providing energy services to consumers, the country needs to urgently introduce development training programs and core courses in Renewable Energy Technologies (RETs).
8) To improve the security of electricity supply, expanding the energy sources in the country, from gas and hydro to solar and wind with the possibilities of nuclear.
9) Other states and local governments must show interest in renewable energy exploration, as is presently the case of Lagos State [18].
10) Table IV below summarizes the major beneficiaries of Solar Power Generation at various stages [13].

TABLE IV
WHO BUYS SOLAR POWER GENERATORS? [13]

| Who? | Where? How? | Motivation |
|---|---|---|
| Home Owners | Domestic roofs | Cut electric costs |
| Councils | Sch buildings etc. | Cut electric costs |
| Corporations | High stake | Gain emission credits |
| Engineers | Developers | Sell electricity |
| Consumer | Citizens | Alternative and reliable |
| Power Companies | National Grid | Spread energy mix |

Unlike other countries, only a state in the North West part of Nigeria has paid attention and issued an initial offer letter for PriVida to establish a 20 MW solar farm in the region.

To show its commitment, the Government allocated 125 acres of land for the project and pledged support for licensing required to facilitate successful execution. Even though PriVida has kicked off a feasibility study in February 2016, the lack of sensitivity and urgency in Nigeria Power Sector is a setback coupled with corrupt practices rooted in the Nigeria Electricity Regulatory Commission (NERC). The outcome creates an unstable supply of electricity and affects economic development [18].

## VII. CONCLUSION

A sturdy, efficient and operating energy sector is a prerequisite to transforming Nigeria into a developed nation. The huge potential and abundance of renewable energy in the country are mostly not yet exploited. Obstacles to this exploitation are due to the presence of large oil and gas production, massive corruption, lack of sensitivity and clarity in the power sector and general known concern of financial support mechanism for renewable energy.

Many countries have embraced decentralization but Nigeria has done the opposite. The 2005 Reform Act on Power sector has shown that all electricity associated with the 36 states in the country and their local government areas must be centrally regulated. Decentralization of the power sector should be the first step out of many ways to solve these problems but could be difficult to achieve due to conflicting laws in the power sector [14].

The Solar generation potential of the Northeastern part of Nigeria alone is capable of powering the entire northeastern region. Although, it lacks the capacity to presently generate enough electricity to support the entire consumers in the country. There could be significant long-lasting benefits from permanently investing in renewable energy across the country, the estimated potential for concentrated solar power, intensity, and photo-voltaic generation is roughly about 427 GW [16].

The energy storage model is PV-based [9] and could be extended and modified to be applicable in other regions of the country. Besides the alternative solution offered by the system, there could be a huge reduction in electricity cost for consumers across the country making it very affordable and most reliable.

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