

Feasibility Studies and Design of a Solar Farm to Supply 4000gwh/Year of Electrical Energy to the Nigerian National Grid

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Abstract

The bulk of the electricity in the Nigeria National Electricity Grid, NNEG, is from natural gas power plants. Since natural gas is an exhaustible source of energy, it is imperative to, while solving Nigeria's energy crisis, increase the contribution of renewable sources to the NNEG. One of the most abundant renewable energy resources in Nigeria is the solar energy. Ironically, this source of energy does not contribute to the NNEG yet. Hence, the aim of this study was to investigate the feasibilities for a solar farm capable of supplying 4000GWh/year (456MW) of electrical energy to the NNEG. To do this, it was set out to design the solar farm by estimating the output from a single solar panel fixed at a chosen location, thereby estimating the number of solar panels needed to give the required output. In addition, the study also intended to design the mounting format, calculate the required land area and estimate the installation and maintenance costs. Using Sun Power's SPR-E20-440-COM solar panel and European Communities' PVGIS online solar energy simulation system and choosing a suitable location, the output of a single fixed panel was calculated to be 714kWh/yr. Hence, considering system losses and other allowances, the number of panels to add 4000GWh/yr or 456MW of electricity to the NNEG was estimated to be 6700000. Furthermore, the mounting format was designed to have four modules per unit of each row. The land area required was, therefore, calculated to be 17.3km² (more than 4 modules per unit would take less space). Thus, 20km² of land was proposed to take care of inverter and transformer installations as well as staff housing. Finally, from the cost analysis of the solar farm based on a 15-year period, the total cost was estimated to be \$546,916,000 (₦196.9b). The solar panel model chosen was designed to have a minimum of 25 years of optimum functionality, making 15 years a safe number for the cost analysis. Hence, the cost of electricity generation from the solar farm for a 15-year period was estimated at \$0.009 per kWh (₦3.28 per kWh). Comparing this to the current cost of electricity generation in Nigeria—more than ₦10 per kWh (\$0.03 per kWh)—this project is deemed very viable. Overall, the findings show that, compared to existing sources, not only is solar energy a better option from the environmental and sustainability points of view, it is also cheaper in the long term.

Keywords: *Renewable energy, Sustainability, Cost, Electricity grid*

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Background to the Study

As the clamour for reduction in the carbon footprints of world energy resources continues, many countries are looking to harness their renewable sources of energy, especially solar energy. African countries are not left out. Morocco, for instance, is building the largest solar farm in the world, the Noor Complex, which when completed will generate 580 MW of electricity (Summers, 2019). Other African countries like Egypt and Rwanda also have functional solar farms. Outside Africa, many countries in Asia and the West are also investing in solar energy. Nigeria, being a tropical country, has an abundance of the sun round the year but there is no solar farm in Nigeria yet (Newman, 2019). Nevertheless, there have been several studies on utilization of solar energy, amongst other renewable energy sources, in Nigeria (Sambo, 2009), (Cloutier, 2011), (Adaramola, 2014), (Bahramara, 2016). A few authors have also proposed and studied the use of solar energy for rural as well as stand-alone electrification (Ayodele, 2014), (Olatomiwa, 2015), (Olatomiwa, 2014). (Adaramola, 2014) particularly studied the viability of grid-connected solar energy system for the city of Jos, Nigeria, while Okoye (2016) examined the solar energy potentials of different cities in Nigeria. However, there has been no outright assessment of the possibility of a high-power solar farm for addition into the national grid. Thus, this study aims to make an original contribution to knowledge by studying the feasibility of establishing a solar farm for the purpose of adding the generated power to the Nigeria national electricity grid and by designing the solar farm. It is a continuation of the global effort to produce sustainable energy, especially without adverse environmental trade-offs.

Site Location

The proposed site for this solar farm is a large vast vacant area of land off Katsina-Daura Road 1) in Katsina State, Nigeria. It's approximately 20 km² in area (explanation for choosing this area is at Section 2). The pinpoint with latitude 12.986157 and longitude 8.037777 (Northern Hemisphere) within the area was used to do the power-generation calculations (see Section 2). The closest major city to it is Katsina (about 43km). This site has been chosen for a number of reasons which include high solar irradiance for Katsina State, Nigeria land being largely unshaded, being close to the Sahara Desert and being close to a major city which enables ease of maintenance.

Solar Energy Calculator Used

After careful investigation of the solar energy calculators available on the web, the European Communities' JRC Photovoltaic Geographical Information System (PVGIS) PV Potential Utility (EC, 2012) has been chosen for this geographic location. Calculators like NREL's SAM and RTScreen (SPS, 2015) could not be used for this location as SAM does not have data for Nigeria while the closest database available on RTScreen to the location is Kaduna and this would lead to unnecessary interpolations. On the other hand, the PVGIS PV Potential Utility has the advantage of being online 2 (thus, always up to date), using interactive maps with accurate irradiance data to pin calculation to exact location.

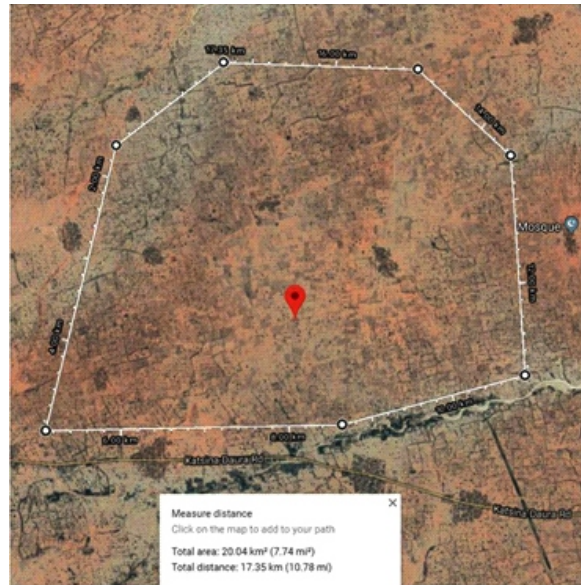


Figure 1: Proposed Site (Google Maps, 2019)

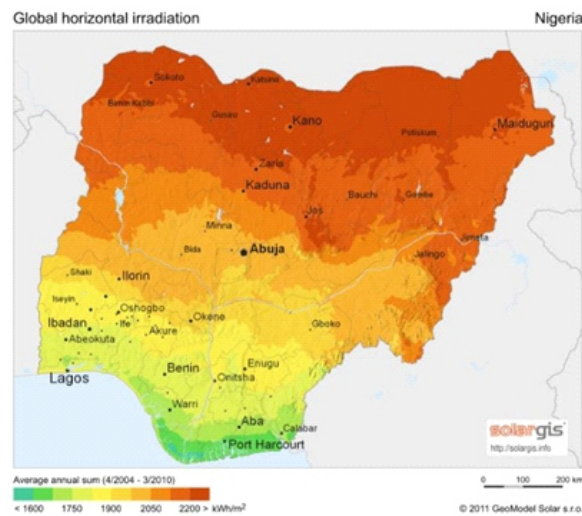


Figure 2: Solar Irradiation for Nigeria (SolarGis, 2011)

Furthermore, it automatically selects the radiation database for the location as well as estimating the system losses ('derate' factor). A comparison between the value of average solar irradiation it uses for a location {example Hm in (a)} and that on irradiation maps shows it is accurate to a large extent. In addition, it also plots necessary graphs (such as shown in to help the user 3 plan well. Also, it generates estimated values of other losses (apart from 'derate' factor, which the user can change since it is the sum of losses from inverter systems, transformers and other devices used, which can be available to the user) and has options for tracking and optimizing inclination and azimuthal angles.

PV Module Choice

After a careful search of the many brands and models of solar modules online [(Sroeco Solar, 2015), (RenSmart, 2015), (PSI, 2015), (Which, 2015), (NREL, 2015)], the SunPower SPR-E20-440-COM model (SunPower, 2015) has been chosen for the solar farm. Based on monocrystalline technology {which is one of the best and commonest for modules, (Evo Energy, 2015)}, this particular module from the very popular SunPower has one of the best power-to-size ratios ($204\text{W}/\text{m}^2$) in the market. None of the solar panels compared in (RenSmart, 2015) comes close to this module in terms of optimal performance. It has a peak power of 440W with an efficiency of 20.3%. It measures 2.067m long and 1.046m wide with a frame thickness of 49mm. With operating temperature range (-40°C to $+85^\circ\text{C}$) suitable for the site location (with average temperature of 25.2°C to 28.6°C , (EB, 2019)), it also has drain holes to help drain rain water. The full details of the specifications of the module are given in (SunPower, 2015). On the financial side, the manufacturing company, SunPower has robust deals for acquiring a large number of their commercial modules (SunPower, 2015). Being a commercial solar panel, the SPR-E20-440-COM is, thus, very suitable for the proposed solar farm. Moreover, as shows, SunPower is one of the most trusted solar module manufacturers (Sroeco Solar, 2015).

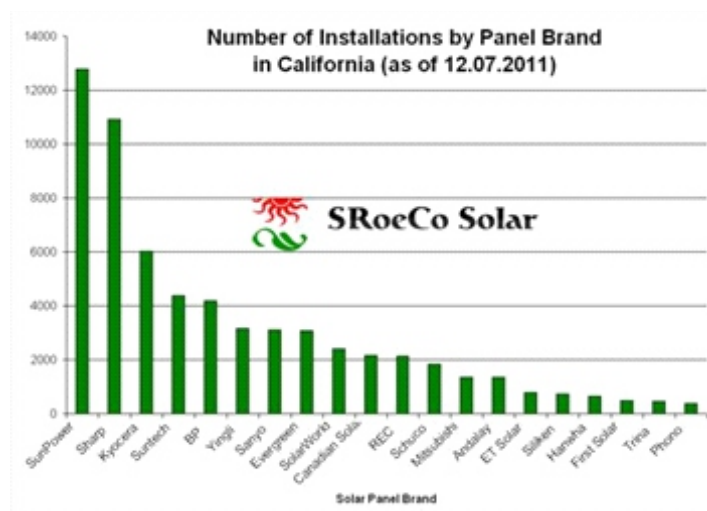


Figure 3: Choosing Solar Panel Brands (Sroeco Solar, 2015)

Calculations

Output for One Module

The inclination angle, α , is required to be inputted into the calculator. This is obtained by performing the following initial calculation:

Polar angle, θ , is gotten from:

$$\text{Latitude (Northern Hemisphere)} = 90^\circ - \theta \text{ (Jäger, 2016)}$$

$$\Rightarrow \theta = 90^\circ - 12.986157^\circ = 77.014^\circ$$

For maximum radiant energy at noon:

$$\theta + \alpha + \theta_d = 90^\circ \quad (\text{Jäger, 2016})$$

Where θ_d is the angle of declination.

For Northern Hemisphere, $\theta_d = -23.5^\circ$ (Jäger, 2016)

$$\Rightarrow \alpha = 90^\circ - 77.014^\circ + 23.5^\circ = 36.486^\circ$$

Taking this to the calculator the output for one module, without optimizing the angle or tracking, is calculated. The calculator has default system losses ('derate' factor) of 14%. This is accepted in this calculation. An output of 680kWh/year for one module is gotten. Recall that 36.486° is the angle for noon. The calculator offers to optimize the angle for the location for the user. This helps to obtain optimum performance for the whole day. This is done by clicking 'optimize slope' and 'also optimize azimuth' in order. The System upon calculation, then generates the optimal values for the angles as shown in This gives a value of 714kWh/year for one module (a).

Since the location experiences almost constant irradiation (b) round the year and has approximately the same average performance for winter and summer months and because the difference in the length of the day (time of appreciable solar irradiation) in the summer (no daylight saving in summer) and that in the winter at the location (in fact, in Nigeria) is very negligible, it is not financially viable to use different inclination angles for winter and summer as this would raise the yearly maintenance costs to a very high value.

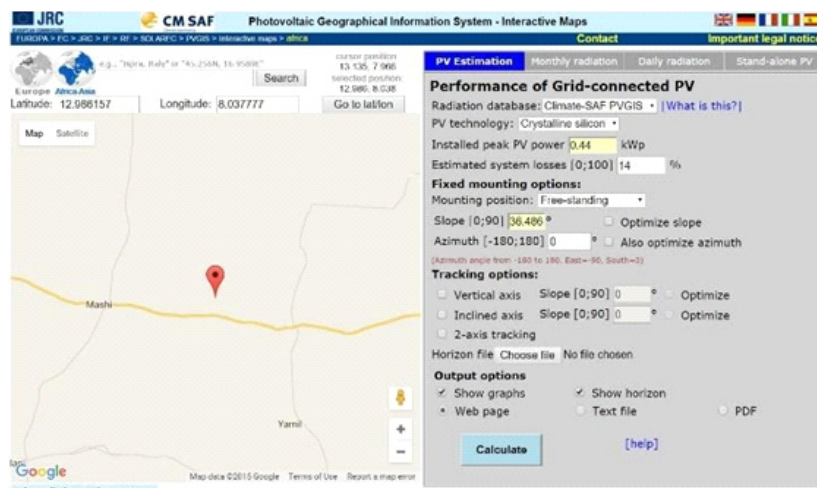


Figure 4: PV Calculator – no optimisation of angles (EC, 2012).

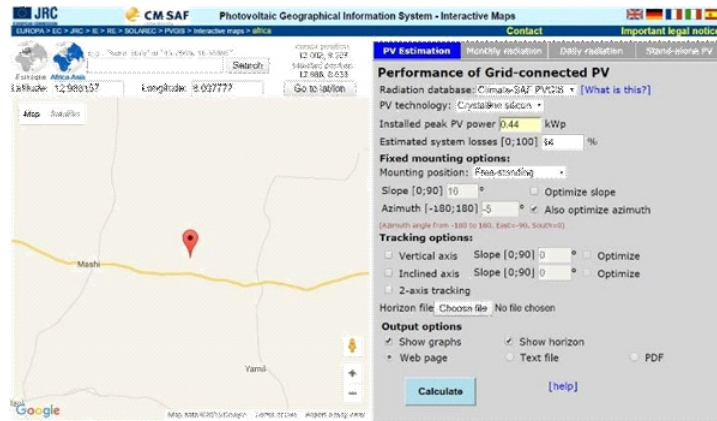
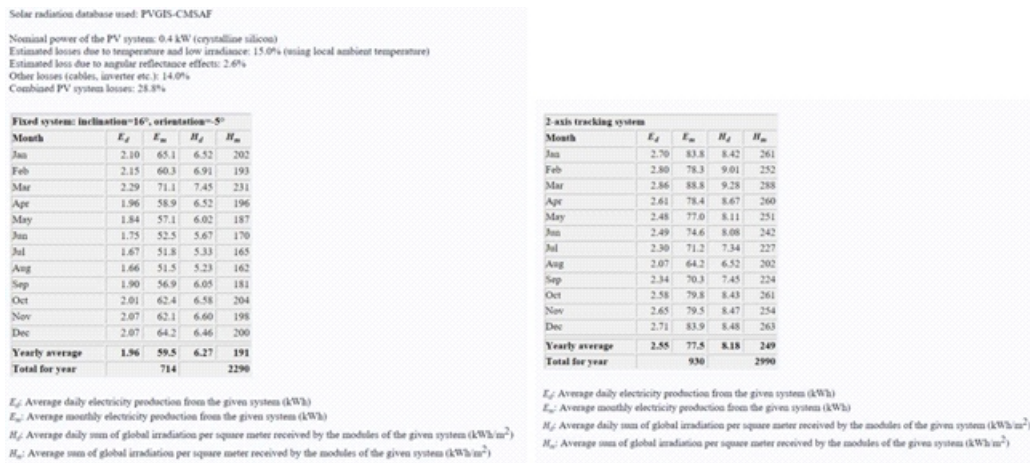


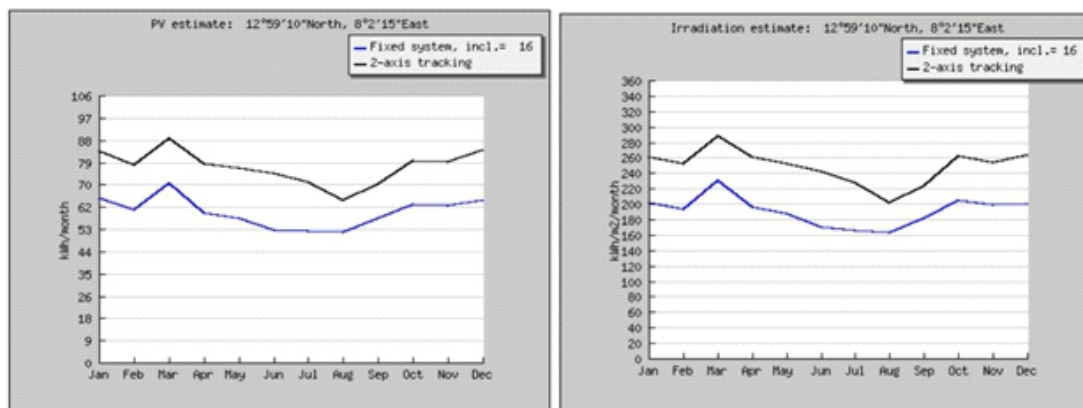
Figure 5: Inclination (slope) and Azimuth optimised (EC, 2012).



(a) Result for optimised angles, no tracking

(b) Result for 2-axis tracking

Figure 6: JRC PV Estimation Utility: Results (EC, 2012)



(a) PV Estimate

(b) Irradiation Estimate

Figure 7: Estimated Results for both fixed system and 2-axis tracking system (EC, 2012)

If 2-axis tracking is opted for, the result is 930kWh/year (b) and black lines of 7}. But doing a financial appraisal of the extra cost of the 2-axis tracking system through The Eco Experts (TEE, 2015) and which (Which, 2015), it is clear that tracking systems cost as much as the modules themselves, if not more. Ergo, the best option for the solar farm is the 714kWh/year output from a fixed system.

Number of Modules to give Required Output

Using this value, the *minimum* number of PV modules to give the total output of 4000GWh/year required is calculated as follows.

$$\text{Number of 440W PV modules required} = \frac{\text{Total Output required}}{\text{Output for one module}} = \frac{4000 \times 10^9 (\text{Wh/yr})}{714 \times 10^3 (\text{Wh/yr})} \approx \mathbf{5602241}$$

Allowances and Feasible Number of Modules to give Required Output

Degradation of PV Cells: The solar module is estimated to work for 25 years without reduction in performance (DeGraaff, 2011). Yet an allowance of 5% for possible degradation is made here (NREL, 2015).

Availability of PV Cells: The availability of the SPR-E2-440-COM with its **associated inverter and transformer systems** is estimated [(SunPower, 2015), (NREL, 2015)] at 94%. This is because, all the units may not operate satisfactorily within the required times for its optimum energy delivery. Again, most solar farms have not run for more than 50 years, hence enough data is not available to give clear ideas of availability of different makes of solar modules. Thus, considering availability, a reduction in overall performance of 6% is assumed.

Being close to the Sahara, wind, dust and other **extreme conditions of weather** is estimated to decrease overall performance by 7%

Total percentage allowance = 18% 7Thus, to get the total number of cells (considering these allowances) we multiply the required output by 118/100 and divide by the output of one cell. That is:

$$\begin{aligned} \text{Total Number of 440W PV modules required} &= \frac{\text{Total Output required} \times \text{allowances}}{\text{Output for one module}} \\ &= \frac{4000 \times 10^9 \times \frac{118}{100}}{714 \times 10^3} \approx \mathbf{6610644} \end{aligned}$$

To cover for **unforeseen losses** or **greater losses than estimated**, this number is rounded off to 6700000 (six million and seven hundred thousand) modules.

Area of Land Required

Using the optimised inclination angle of 16°, we calculate the minimum spacing between rows of the modules as follows:

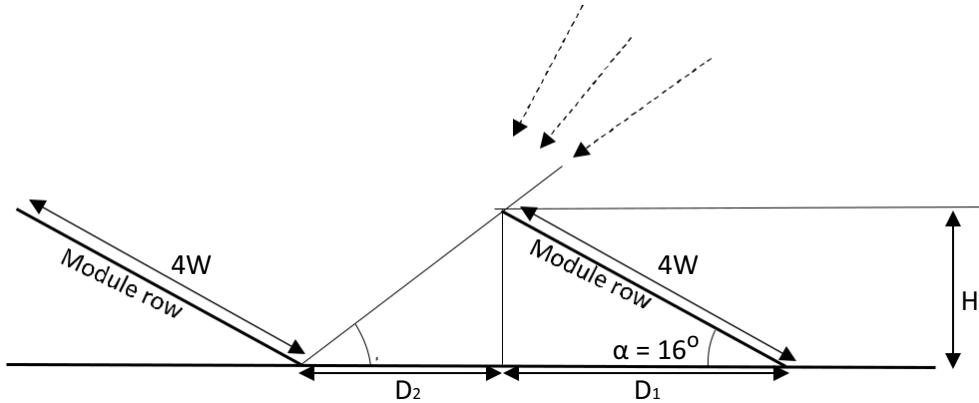


Figure 8: Layout of solar module arrangement (Jäger, 2016)

From Fig. 6, the minimum spacing, $D_1 + D_2$, is:

$$D_1 + D_2 = 4W \cdot \cos\alpha + H \cdot \cot\beta = 4W \cdot \cos\alpha + 4W \cdot \sin\alpha \cdot \cot\beta \text{ (where } H = 4W \cdot \sin\alpha\text{)}$$

Where $4W$ is from the fact that four panels are proposed to make one row, lying width-wise (see Fig. 9)

For extreme conditions of angle of declination of the sun, i.e -23.5° for Northern Hemisphere, (Jäger, 2016),

$$\beta = \theta - 23.5^\circ = 77.014 - 23.5^\circ = 53.514^\circ$$

$$\therefore D_1 + D_2 = 4.184 \cdot \cos 16^\circ + 4.184 \cdot \sin 16^\circ \cdot \cot 53.514^\circ \approx 4.87m$$

(Note that using $\alpha = 36.486^\circ$ will give a smaller distance and that β is not a function of α)

To make further room for manual maintenance and to completely ensure no shading, this spacing is rounded off to 5m. Thus, the area taken by one module is:

$$\text{area taken by 4 modules} = \text{spacing} \times \text{length of module} = 5m \times 2.067m = 10.335m^2$$

Thus, the total area taken by all the modules in the solar farm is estimated:

$$\text{Total area} = \text{area of 4 modules} \times \frac{\text{number of modules}}{4} = 10.335m^2 \times \frac{6700000}{4} = 17311125m^2$$

This converts to **17.3km²**.

However, to allow for space between adjacent rows, space for accompanying installations like inverter and transformer systems, shelter for security (and other resident) personnel and space for possible increment in the number of modules in the future, **20km²** of land {Fig. 1 (a)} is proposed.



Figure 9: Proposed mounting format (Roth, 2017).

External Factors and Cost Analysis

Environmental Impact

Although this project would not cause significant noise pollution or other forms of pollution, there are bound to be a few impacts to the immediate environment. Firstly, in order to get the land prepared for the project, some trees and shrubs will be cut down, causing some level of **deforestation**. In addition, since most vacant lands in Katsina state are used for **farming and animal grazing** (EB, 2019), the farmers in nearby towns are bound to have concerns over the project. Thus, **at the initial stage** of the project, **after acquiring the land**, stakeholder consultations would be very necessary. Incentives like indigenous recruitment for selected positions, royalties among others could be proposed.

Estimate of Costs for a 15-Year Life Span

This project is 'capital-intensive' in that it takes a lot of money to install. However, it has very low maintenance costs as compared to the traditional energy sources. Thus, with increasing production years, the cost of producing of energy via this source is bound to become much cheaper. In this section, the cost of generating electricity (to the tune of 4000GWh/year) through this solar farm is estimated. Table 1 enumerates the estimated costs for the different aspects of the project. 'Salaries of Dedicated Staff' include payment for local security personnel, cleaners and other contract staff. 'Contingency Costs' are costs of expenses arising from unforeseen circumstances and repair works. These are estimates only and actual costs may vary considerably. Company commercial quantity price of \$80 per module (company price) has been estimated with a delivery cost of \$4000 for all modules. Other estimates are as in Table 1.

Table 1: Estimate of Costs [(SunPower, 2015), (BRE, 2015), (TEE, 2015), (Which, 2015) and (PV Magazine, 2015)

Capital Costs		Maintenance Costs	
Item/Activity	Cost (\$)	Item/Activity	Cost (\$/yr)
6700000 Solar Modules and Delivery	536,000,000	Equipment Maintenance	10,000
Inverter and Transformer Systems	10,000,000	Salaries of Dedicated Staff	30,000
Other Equipment	50,000	Contingency Costs	10,000
Transportations	4,000		
Installations	82,000		
Fencing, Lighting and Access Control Gadgets	30,000		
Total	546,166,000	Total	50,000

Thus, the cost of generating 150GWh/year of electricity for a 15-year life span is:

$$\begin{aligned} \text{Cost of 15year powergeneration} &= \text{total capital costs} + (\text{maintenance costs} \times 15) \\ &= \$546,166,000 + (\$50,000/\text{yr} \times 15\text{yrs}) = \mathbf{\$546,916,000} \end{aligned}$$

This converts to ₦196.9b (at ₦360 to the USD) for generating $4000 \times 15 = 60000$ GWh of electrical energy. This is equivalent to a production cost of $(\text{₦}196.9 \times 10^9) / (60000 \times 10^6 \text{kWh}) = \text{₦}3.28/\text{kWh}$ (i.e. \$0.009/kWh) (based on a 15-year life span) which goes lower with increasing years owing to the fact that the maintenance costs per year are minimal. Meanwhile, electricity in Nigeria (in recent times) is charged in excess of ₦20/kWh (\$0.06/kWh) at consumer level with a production cost that is a little in excess of ₦10/kWh (\$0.03/kWh) (Ofoegbu, 2013).

Grants Available for Capital Cost of Installation and other Incentives Available for the Project

The global community is enthusiastic about 'green' energy because of the many environmental problems posed by the traditional fossil-based sources of energy. Thus, efforts are in place all over the world to encourage investment in renewable energy sources. Therefore, the following grants and incentives are can be explored for the purpose of this project.

1. World Bank (2015): Financing Renewable Energy: Options for Developing Financing Instruments Using Public Funds → towards capital cost of installation.
2. UNDP-Nigeria (2015): Renewable Energy Grants → upon partnership with the Nigeria government, towards capital cost.
3. Nigerian government's eagerness to partner with private companies to improve power supply incentive for alternative energy and improvement in energy supply (PWC, 2015).

Summary/Conclusions

The forgoing is a feasibility study and design of a 4000GWh/year (456 MW) solar farm. An estimate of the number of units of solar modules required to give this output has been put at 6700000. About 20km² of land will be required for this project. Thus, a vacant land measuring 20.04km² and a little off the Daura-Katsina Road has been proposed for this project. Going further, the environmental impacts of the project has been assessed and found to be minimal even though farmers or land lease-holders (or owners) at the location will have to be consulted and compensated. Finally, an estimate of the cost of the project has been made as well as its maintenance costs per year. Using this, the cost of electricity production from the solar farm based on a 15-year life span has been estimated at ₦3.28/kWh (i.e. \$0.009/kWh). This value is quite less than the current electricity production cost of at least \$0.03/kWh in Nigeria. Recall that solar energy does not contribute to the national electricity grid of Nigeria yet. Thus, this project is deemed essential and viable.

Further Studies

Further studies can be conducted based on or in furtherance of this study. The following are deemed points of further studies and discussions:

- i. If a solar panel of higher capacity is chosen, the number of panels required to generate the same amount of energy will reduce and so will the land area required.
- ii. The choice of solar-panel is based on what is available at the time of this study. Further economic considerations can lead to a better choice. This would lead to recalculation of the electrical output and the land area.
- iii. The mounting format can also be altered to take more than four modules per row, leading to reduction in total land area required.
- iv. An optimal angle of inclination of 16° gotten from the online calculator has been used. Using the alternative, 36.486°, gotten from first principle, will make the farm more compact and save space although this will affect the total output.
- v. It would be interesting to look at a solar farm with tracking systems, especially from the perspective of costs

Symbols and Notations

Symbol	Meaning	Symbol	Meaning
θ	Polar Angle	β	Minimum angle of shadow of module row to the ground
α	Angle of Inclination of Module	L	Length (or height) of module
θ_d	Angle of Declination of the Sun	D1+D2	Minimum space between successive module rows
φ	Azimuthal Angle	H	Vertical height of module row

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