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Research/Technical Note

Estimating the Solar Home System Sizing for Rural Residential Apartments Using a Panel Tilt Angle of 82 Degrees: Ilorin, Kwara State as Case Study

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Abstract: Nigeria is blessed with abundant sunshine and as such there is an enormous potential for the utilization of solar energy all across the nation. Ilorin, Kwara State is among the North-Central regions in Nigeria and has a latitude and longitude of 8.4799oN and 4.5418oE respectively with a land area of about 765 sq. km. and an elevation of 307.4m above sea level making it one of such locations in the nation having a good solar irradiation. Solar irradiation in Nigeria varies according to location and for different times of the year according to the weather and climate of such locations. As such depending on the tilt or orientation of the solar panels with respect to the sun, the solar irradiation hitting the solar panels differs. This paper using a solar system configuration where the solar panels direction is positioned facing directly south and having a tilt angle of 82 degrees seeks to provide a prototype for the design of a solar energy system whereby residential apartments especially 2-bedrooms in rural locations having no access to the nation's electricity grid could have a better, cleaner and more efficient alternative source of energy.

Keywords: Solar PV Modules, Solar Irradiation, Battery-Banks, Inverters, Panel Generating Factor, Solar Controllers, Tilt Angle

1. Introduction

The world is now taking quantum leaps into power generation using Renewable energy sources. This transition is partly due to the alarming rise in Green House Gases which are already negatively affecting the climate in the world and recently around December 2015, the United Nations Framework Convention on climate Change (UNFCCC) Europe led by Paris came up with a Paris Agreement for the world in which countries would devise means and strategies to help curtail global warming to well below 2 degrees Celsius by 2030 [1]. 195 countries have signed and agreed to this and Nigeria on 22nd September 2016 did same led by her President, Mohammadu Buhari [1, 2]. Also, the necessity for efficient power generation gives rise to alternative power sources which are renewable e.g. Solar, Wind, Biomass, Geothermal, Tidal and Hydropower which are all natural and self-replenishing as opposed to fossil fuels which are quite expensive with lots of negative side effects. These are some of the reasons why this transition is moving fast globally and Nigeria has to double her efforts in her energy sector if she's to improve her economy and have sustainable energy for the future.

The debilitating state of power in the nation right now is really disheartening. As every day, more and more businesses die or are at a standstill because of the erratic power situation in the country. According to the National Control Centre (NCC) Oshogbo Osun State report, as at 15th Mar 2017, Nigeria's average power generated/sent out was 3720MWh/hour which is way less than its installed capacity at 12,522MW servicing a population of over 160 million people with a majority living on less than US$2 a day. This is definitely not enough and as a result about 54.7% of Nigerians don't have access to electricity especially those residing in rural areas [3].

About 1.4 billion people around the world still do not have access to the regular electricity. It is estimated that roughly 85% of the people without electricity live in rural, semi-urban or remote rural areas of the sub-Saharan Africa and South Asia [4]. In Nigeria, residential electrification accounts for 57.3% of the total electricity generated in the Nation, while 26.1% and 16.6% account for commercial and industrial use [5]. Hence, even those who do have access to electricity, don't have it in stable supply. The Distribution Companies (DISCO's) in Nigeria instead implement a technique called load shedding where some places/communities are supplied electricity for a particular time period to the detriment of other communities. And even these sometimes in some locations is very poor as sometimes the quality of power supplied is really no different than having no electricity at all.

A study conducted in Bangladesh concluded that if Solar Home System (SHS) is used according to the designed and installed specification, it can improve the quality of life of rural people and provide Income-generating opportunities [6]. Also, the results of a survey conducted in Fiji indicate that SHS has improved quality of lives, provided entertainment, enabled increased working and study hours and created jobs, contributing directly and indirectly to increased income generation for the households using it [7]. Substantial expansion in quantity, quality and access to infrastructure services, especially electricity, is fundamental to rapid and sustained economic growth, and poverty reduction. The electricity industry, dominated on the supply side by the state-owned electricity utility, National Electric Power Authority (NEPA), and succeeded by the Power Holding Company of Nigeria (PHCN), has been unable to provide and maintain acceptable minimum standards of service reliability, accessibility and availability [8].

But nonetheless, Nigeria is one country in the world where solar energy is available but its potential has been greatly untapped. Although the solar irradiation varies all through the year in Nigeria, it's recorded that the average daily solar irradiation per square meter in Nigeria is about 5.25kwh with an average estimated sunshine hour of 6.5 hours [9] and receives on the average 20MJ/m2 per day of solar insolation depending on the time of the year and the location considered [9] [10].

Solar energy is the light and radiant from the Sun that influences earth's climate and weather. It is the source of energy that sustains life in the earth planet. Solar radiation along with secondary solar resources such as wind and wave power, hydroelectricity and biomass accounts for over 99.97% of the available flow of renewable energy on earth. According to this source, the earth receives 174 petawatts (PW) of incoming solar radiation known as insolation at the upper atmosphere [11].

The current generation of solar PV in Nigeria is 15 MW, which consists only of micro and off-grid solutions, as no utility-scale project is connected to the grid yet. Still the need to power the rural and remote areas of Nigeria has given birth to several Micro-grid solar PV projects [12].

There has been an energy policy in place in Nigeria since 2006, called the Renewable Energy Master Plan (REMP). The policy was implemented to increase the share of renewables to account for 10% of Nigerian total energy consumption by 2025. The plan includes an installed capacity target of 500 MW by 2025. Nigeria's power minister has mentioned the ministry aims to boost the installed capacity of solar PV to 1 GW over the next 10 years [12].

Although there has been some other school of thought opposed to the notion that using SHS for rural electrification is worthwhile; one of such thoughts lay claims to one challenge which is that SHS is limited in scope as basic energy needs like cooking cannot be met [13]. Also, besides the low power capacity of SHS, the energy conversion efficiency is low and can easily be affected by the deposition of dusts and other elements on the panel [14].

Off-grid systems based on PV and batteries are becoming a solution of great interest for rural electrification. Nevertheless, sizing these systems is not straightforward since it means matching unpredictable energy sources with uncertain demands while providing the best reliability and costs [15].

Hussein A et. al (2013) in their work described a method for optimal sizing of a standalone PV system for remote areas in Sohar, Oman where Numerical methods for optimization of the PV module tilt angle, PV array size and storage battery capacity are implemented using MATLAB and hourly meteorological data and load demand[16].

Similarly, Pietro Elia Campana et. al (2016) in their work developed an open-source software that service providers can use to optimally design SHSs components based on the specific electricity requirements of the end-user. This was written in MS Excel-VBA and calculates the optimal SHSs components capacities guaranteeing the minimum costs and the maximum system reliability and the results obtained with the developed tool showed good agreement with a commercial software and a computational code used in research activities [17].

In addressing the effect of load profile uncertainty on the off-grid PV systems, Stefano Mandelli et. al (2016) in their work addressed and analyzed the effect of load profile uncertainty on the off-grid PV systems optimum design. Specifically a novel sizing methodology has been introduced based on: (i) an effective approach of modelling rural energy needs; (ii) an innovative stochastic method which formulates different possible realistic daily load profiles for un-electrified rural areas; (iii) a PV battery techno-economic analysis via steady-state simulation; (iv) the evaluation of the optimum system sizing via a numerical method based on net present cost and loss of load probability with their methodology being tested in a peri-urban area of Uganda [18].

The prototype this paper addresses would facilitate a correct estimate of the size and specifications of solar system components for rural residential apartments without access to the nation's electricity grid. Using common household appliances found in a typical 2-bedroom apartment; the solar PV system components sizing is determined. This has a number of advantages, among which are:

(1) Deployment of a clean source of energy devoid of noise and environmental pollution.
(2) Reduction in dependability on the National grid supply of electricity.
(3) Stability of Generated power.
(4) Dependability on power generation.
(5) Cost benefits to using other source of power generation (Diesel/PHCN) etc.

2. Solar Irradiance

Solar Irradiance is a measure of the amount of solar power gotten at your location. This irradiance varies throughout the year depending on the seasons. It also varies throughout the day, depending on the position of the sun in the sky, and the weather [19]. Solar irradiance could also be defined as the power per unit area received from the Sun in the form of electromagnetic radiation in the wavelength range of the measuring instrument. Irradiance may be measured in space or at the Earth's surface after atmospheric absorption and scattering. It is measured perpendicular to the incoming sunlight. Irradiance is a function of distance from the Sun, the solar cycle, and cross-cycle changes. Irradiance on Earth is also measured perpendicular to the incoming sunlight [20].

The sunlight covers a broad range of wavelengths from roughly 250 nm (UV) over the visible range (400-700 nm) up to several thousands of nm (IR). The radiation density is decreasing with the square of the distance. At the average distance of the earth from the sun, the flux of energy amounts to 1366 W/m^2 which is called the solar constant [21]. On the way through the atmosphere the properties of the irradiation are slightly changed; e.g. the UV light is absorbed by the ozone layer, some parts of the IR are absorbed by water vapor and carbon dioxide. Depending on the latitude of the observer, the irradiation density is still lower due to the longer path of sunlight through the atmosphere, e.g. to below 1000 W/m^2 in Central Europe [21].

The solar irradiation data for Ilorin, Kwara State as obtained from [22] over a 22-year period providing monthly average insolation figures are as tabulated below:

Using the data obtained from Table 1, the plot for the solar irradiation against months in Ilorin for the tilt angle and direction is as shown in figure 1 below:

Table 1. *Solar Irradiation against months for Ilorin at 82° facing directly south.*

S/N	Months	Solar Irradiation (kwh/m^2/day)
1	Jan	6.44
2	Feb	6.19
3	Mar	5.92
4	Apr	5.40
5	May	5.27
6	Jun	4.79
7	Jul	4.13
8	Aug	3.78
9	Sep	4.13
10	Oct	4.99
11	Nov	6.06
12	Dec	6.47
Total =		63.57
Average =		5.30

Source: http://solarelectricityhandbook.com/solar-irradiance.html

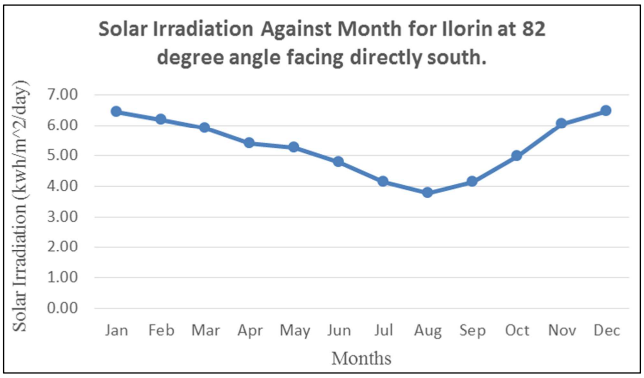

Fig. 1. *Solar Irradiation against Months.*

3. Materials and Methods

For the appropriate estimate of required energy consumed in a typical 2-bedroom apartment, field trips were undertaken randomly to newly constructed 2-bedroom apartments among which is the new 2-bedroom apartment in Landmark University, Omu-Aran, Kwara State. Table 2 below outlines in details, the power and energy consumption of typical equipment that could be found in the home of an average family residing in a 2-bedroom apartment. The power ratings used for the various appliances are based on different type of manufacturers as such a minimum and maximum value was retrieved and the average computed and used.

Table 2. *Power and Energy Estimate of a typical 2-bedroom apartment in Ilorin, Kwara State.*

S/No	Appliances	Minimum (W)	Maximum (W)	AVG (W)	Nos	Total Wattage (KW)	Hours of Usage per week	Total Wattage-hours (kWh/wk.)
1	Ceiling fans	25	75	50	4	0.2	80	16
2	25" Television	150	150	150	1	0.15	50	7.5
3	Laptop PC	50	100	75	2	0.15	40	6
4	Microwave	600	1700	1150	1	1.15	7	8.05
5	Electric Toaster	800	1800	1300	1	1.3	3	3.9
6	Washing Machine	500	500	500	1	0.5	5	2.5
7	Tablet Charger	10	15	12.5	2	0.025	14	0.35
8	Phone Charger	4	7	5.5	2	0.011	14	0.154
9	Electric Iron	1000	1000	1000	1	1	4	4

S/No	Appliances	Minimum (W)	Maximum (W)	AVG (W)	Nos	Total Wattage (KW)	Hours of Usage per week	Total Wattage-hours (kWh/wk.)
10	Refrigerator/Freezer	150	400	275	2	0.55	84	46.2
11	Food/Juice Blender	300	400	350	1	0.35	2	0.7
12	Electric Kettle	1200	3000	2100	1	2.1	4	8.4
13	Electric Shaver	15	20	17.5	1	0.0175	2	0.035
14	Hair Blow Dryer	1800	2500	2150	1	2.15	4	8.6
15	CFL's	11	18	14.5	10	0.145	56	8.12
Total		6,615	11,685	9,150	31	9.7985	369	120.509

Table 2 above reveals the total energy consumed per week. This energy consumption is as a result of the load mix comprising both low and high power consuming appliances which were left in operation for stipulated number of hours. As seen from the table 2 above, the total energy consumed per week is approximately 121kwh and with some little calculation, the total energy consumed per day is approximately 17kwh. Using this energy deduction, in order to determine the solar system home sizing for the 2-bedroom apartments, a systematic and sequential approach was adopted starting from the determination of the power consumption demand to the batteries needed to support this design.

3.1. Determining the Power Consumption Demand

As was demonstrated in table 2, the total watt-hour per day consumed by the appliances was determined. Following this is the need to also ascertain the total watt-hours per day needed from the PV modules. In determining this according to [23], we took into account wiring connection losses (10%) and battery losses (20%) totaling 30%. Hence, about 130% of energy is required by the appliances to be supplied by the solar modules.

Therefore, multiplying the total watt-hour computed per day by 1.3 results in the total watt-hour per day which must be supplied by the solar panels.

Hence, total energy needed from solar PV panels is 17000 × 1.3 = 22100wh/day or 22.1kwh/day

3.2. Size of the PV Modules

In estimating the total watt-peak rating needed for the PV modules to operate the home appliances, the total watt-hours per day needed from the PV module as discussed in section 3.1 above is divided by the panel generating factor. Just as the solar irradiation varies for different locations, so does the panel generating factor. The panel generating factor is obtained by taking into consideration the correction factor for a solar PV module. The correction factor for a single solar PV module in reality are given as [24]:

(1) 15% for temperature above 25 C
(2) 5% for losses due to sunlight not striking the panel straight on (caused by glass having increasing reflectance at lower angles of incidence)
(3) 10% for losses due to not receiving energy at the maximum power point (not present if there is a MPPT controller)
(4) 5% allowance for dirt
(5) 10% allowance for the panel being below specification and for ageing

Where the panel generating factor (PGF) is given by the following formula:

$$\text{PGF} = \text{Solar Irradiation} \times \text{Total correction factor on the solar panels} \tag{1}$$

For this paper, we use an MPPT solar controller and hence the 10% loss due to not receiving energy at the maximum power point is eliminated, therefore the total correction factor is given by:

$$0.85 \times 0.95 \times 0.95 \times 0.90 = 0.69$$

From table 1, it is seen that the average solar irradiation in Ilorin, Kwara State is given by 5.30kwh/m^2/day. Therefore, the panel generating factor (PGF) = 0.69 × 5.30 = 3.657 ≈ 3.66

$$\text{Given that total } W_p \text{ of PV panel capacity needed} = \frac{\text{Total pv watt-hour needed per day}}{\text{panel generating factor}} \tag{2}$$

$$\text{Hence Total } W_p \text{ of PV panel capacity} = \frac{22{,}100}{3.66} = 6{,}038.3W_p$$

For this paper, we assume the use of a 300watts solar panel, hence to determine the total number of PV panels needed, the total W_p of PV panel capacity is divided by the capacity of a single solar panel which in our case is 300watts.

$$\text{Hence total number of PV panels needed} = \frac{6{,}038.3}{300} = 20.13 \approx 20 \text{ solar PV modules.}$$

Therefore, each 2-bedroom apartment would need to be powered by at least twenty (20) solar PV modules of 300watts capacity. It should be noted that if more PV modules are installed, then the system would perform better and battery life would significantly improve but if fewer PV modules are used, the system may not work at all during cloudy periods and battery life would be shortened.

3.3. Inverter Sizing

An inverter is needed in the solar home system to change the DC input signal from the battery to its appropriate AC signal for the power outlets.

For the inverter sizing, the input rating of the inverter should never be lower than the total watt of the appliances. The inverter must have the same nominal voltage as the battery used. Since, we are looking at a stand-alone system, the inverter must be large enough to handle the total watts that would be used at one time. As such, the inverter size should be 25 – 30% bigger than the total watts of appliances. In case appliance type is motor or compressor, the inverter size should be minimum 3 times the capacity of those appliances and must be added to the inverter capacity to handle surge current during starting.

$$\text{Inverter size} = \text{Total wattage of appliance} + (0.30 \times \text{Total watts of appliance}) \tag{3}$$

Given total wattage of appliances = 9.7985kw

Therefore,

$$\text{Inverter size} = 9.7985 + (0.30 \times 9.7985) = 12.738 \approx 13\text{kw}.$$

The non-linearity's of the loads in the 2-bedroom apartments introduces harmonics and distortions in the current waveform of the system making the current lag behind the voltage and resulting in a low power factor. Details about the causes of low power factor is beyond the scope of this paper. When the resultant power factor due to all the appliances in the home is too low, it increases the apparent power needed and hence the inverter must supply more power to offset the reactive power consumed by the inductive loads in the apartment.

$$\text{Apparent power} = \frac{\text{Real Power}}{\text{Power factor}} \tag{4}$$

For our design, we assumed a power factor of 0.8, hence the apparent power needed is given by:

$$\text{Apparent power} = \frac{13{,}000}{0.8} = 16{,}250 \approx 16\text{KVA}.$$

Hence, an inverter size of between 16KVA and 20KVA at 48volts could be used for this solar system design.

3.4. Battery Sizing

The battery type recommended for using in Solar PV system is deep cycle battery. Deep cycle batteries are specifically designed to be discharged to low levels and rapidly charged day after day for years. The battery should be large enough to store sufficient energy to operate the appliances at night and cloudy days. The battery capacity needed for a solar installation is as given below:

$$\text{Battery capacity (Ah)} = \frac{\text{Total Watt-hour per day used by appliances}}{(0.85 * 0.5 * \text{nominal battery voltage})} \times \text{Days of Autonomy} \tag{5}$$

Where 0.85 is the loss value given a battery loss of 15% and 0.5 is the value for a 50% depth of discharge of the battery. For this paper, we considered using a nominal battery voltage of 48v with a one (1) day of autonomy. The days of autonomy is the number of days we need the system operating when there is no power produced by the solar PV panels.

Therefore, given the total watt-hour per day used by the appliances in the 2-bedroom apartment to be 17kwh, the battery capacity could be calculated thus:

$$\text{Battery capacity (Ah)} = \frac{17{,}000}{(0.85 * 0.5 * 48)} \times 1 = 833.3 \approx 833\text{Ah}$$

Using readily available batteries of 200Ah at 12v, we would therefore have a total of approximately four (4) battery banks where each bank comprises of four (4) sets of 200Ah, 12v batteries.

3.5. Solar Charge Controller Sizing

The solar charge controller is typically rated against amperage and voltage capacities. The Solar charge controller is selected to match the voltage of PV arrays and batteries which then enables the selection of the right solar controller for our solar home system design.

According to standard practice, the sizing of solar charge controllers is to take the short circuit current (Isc) of the PV array and multiply it by a safety factor of 1.25.

$$\text{Solar charge controller rating} = \text{Short circuit current of PV module} \times \text{modules in parallel} \times 1.25 \tag{6}$$

The paper is based on a 48v solar system design. The voltage rating of a typical 300w monocrystalline solar panels is 24v. From preceding computations, it was established that a single 2-bedroom apartment needs at least twenty (20) solar modules. Hence to obtain our desired designed, we paralleled in ten (10) places pairs of solar modules connected in series. In other words, the series connected pair added up to realize the 48v and we paralleled ten (10) of such pairs to result in the twenty solar modules needed to make up our solar array. The specifications of the panels could vary based on the proposed vendor but in this paper, we make use of the Canadian solar CS6X-300-M 300w 24v monocrystalline panel having the following specifications [25].

(1) Nominal Max Power (Pmax) = 300 watts
(2) Optimum Operating Voltage (Vmp) = 36.5 V
(3) Optimum Operating Current (Imp) = 8.22 A

(4) Open Circuit Voltage (Voc) = 45 V
(5) Short Circuit Current (Isc) = 8.74A

Our solar array comprises ten (10) pairs of solar modules in parallel and from the above specifications, it is seen that the short circuit current (Isc) for a single module is 8.74Amps.

Therefore, from equation 6;

$$\text{Solar charge controller rating} = 8.74 \times 10 \times 1.25 = 109.25 \approx 110\text{Amps}$$

Hence, for a single 2-bedroom apartment, our solar home system design would be needing a controller with a minimum rating of approximately 110 amperes.

4. Techno-Economics of Solar Energy in Rural Areas

Compared to other conventional/alternative source of energy in rural communities, solar electricity proves the most reliable and cost saving in the long run. At present in Nigeria, the prevailing market price for a liter of premium motor spirit (PMS) commonly called petrol for running a generator is at the rate of 145 naira per liter [26] and diesel at the rate of 180 naira per liter [27]. With this cost in mind and the fact that over half of Nigeria's population; about 52% live in rural settlements [28], table 3 below shows the cost estimates of using petrol and diesel at an average of 8 hours per day for an entire year.

Table 3. *Cost estimate of energizing a 2-bedroom apartment with a petrol/diesel generator for 1 year in rural areas in Ilorin not connected to the nation's grid.*

Fuel	Hours/day	Price/liter (#)	Qty in liters	Total cost per year (#)
Petrol	8	145	8	423,400
Diesel	8	180	6	394,200

As can be seen from table 3 above, every year a total of about 423,400 naira would be spent on petrol generators for powering the apartments and about 394,200 naira on diesel generators. It should be noted that this costs deduction did not take into account the obvious cost of purchase of the generators and the periodic maintenance that would be necessary for their smooth operations.

Even though the initial costs of installation of the solar home system may be quite capital intensive, nevertheless in ten (10) to fifteen (15) years the individual or government could break-even for his energy needs and given the long-life span of over forty (40) years for solar PV systems.

5. Results

Using the collated data of the appliances available in a typical 2-bedroom apartment, we designed a solar home system sizing prototype for rural residential areas. Table 4 below shows the summary of our analysis.

Table 4. *Summary of solar home system requirements for a single 2-bedroom apartment.*

System Sizing	Values
Energy Consumption per day	17kwh
Solar PV energy needed per day	22.1kwh
Panel generation factor	3.66
Total watt-peak of PV panel capacity needed	6,038.3W_p
Total number of PV panels needed	20.13 ≈ 20 solar pv modules.
Inverter sizing	16 – 20KVA
Battery sizing	833Ah; 4 battery banks comprising 4 sets of 200Ah batteries at 12v
Solar charge controller sizing	109.25 ≈ 110Amps

6. Conclusion

The economic growth and stability of any nation largely depends on the growth and advancement of its energy sector. Little wonder a nation such as Singapore is fast becoming a reference point among nations and fast attaining global attention daily partly because of her huge investment for a buoyant energy sector. No doubt, Nigeria has abundant sunshine and huge potential for the wide deployment of solar power across the nation most especially rural areas without access to the nation's grid.

As such this paper was written to serve as guide for individual investors and the government, especially those of Ilorin, Kwara State in the hopes of providing an alternate source of power for upcoming residential apartments. This paper should serve as a prototype that could be scaled to include whatever number of apartment as may be desired. Hence the results obtained above need only be multiplied by any number of buildings as may be required.

Also, as shown in the techno-economic section, although the initial cost implication of having this solar home setup may be huge, but compared to using petrol or diesel generators over a ten (10) to fifteen (15) year period, the investor would not only break-even but little or no maintenance may be required by the solar system during the entire period. In contrast a petrol or diesel generator may not even last that long as efficiency decreases as utilization increases meanwhile the solar panels have typical life-spans of up to forty (40) years and may even last longer with proper maintenance.

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