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Techno–Economic Viability of Commercial-Scale Photovoltaic Solar-Powered Mini–Grid Systems in Sub-Saharan Africa

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Abstract

Sub-Saharan Africa is currently the darkest part of the world socioeconomically despite having the most solar energy potential globally with half a billion people lacking access to electricity and Nigeria contributing the biggest share resulting in huge unemployment rates, famine, infant mortality, insecurity, low human development index, and political instability among other hydra headed problems. This research aims to probe the commercial viability of solar-powered mini-grid systems for sustainable electricity generation in Sub-Saharan Africa, using Southwest Nigeria as a case study, given its median geographical and geopolitical environment in the region. This is against the background that over 97% of solar mini-grid projects in Sub-Saharan Africa have failed within 5years or are being propped up by external funding instead of being commercially self-sustaining. The 2000 to 2021 solar energy data for 23 locations across Southwest, Nigeria, were obtained from the Langley Research Center, the National Renewable Energy Laboratory, and the Nigerian Meteorological Agency, in addition to scant and isolated data as comparators. the mean mainland and offshore (Bight of Benin) All Sky Solar Insolation was 4.7KWH/m2/day and 4.9KWH/m2/day. A hypothetical 100kW solar mini-grid system was designed and optimally computed with HOMER simulation, MATLAB Simulink, and TELCOE evaluation, which yielded competitive values of \$0.0137/kWh, \$0.018928/kWh, and \$0.019633/kWh, respectively. The system was finally tested by computing the Techno-Economic Renewable Energy Viability Index (TEREVI), which gave a very high value of 0.850911, well above the 0.60 threshold for the region. This conclusively shows that solar photovoltaic energy mini-grid in standalone or hybrid configuration or catenated clusters is commercially viable with the use of a proper comprehensive modeling technique, such as TEREVI, for planning and decision making, as well as keeping the grid capacity within optimal limits

Keyword: solar photovoltaic (PV), mini–grid, Battery Energy Storage System (BESS), Southwest Nigeria, Sub-Saharan Africa, TEREVI, TELCOE.

1.0. Introduction

Africa holds 60% of global solar insolation but attracts less than 2.5% of investment in solar energy development despite needing at least \$200billion annually in the next 20years to connect a minimum of 70% of 650 million of its population currently without electricity access. Similarly, while 1% of Nigeria is worth over 500,000MW of solar energy y but solar energy has no contribution to the national grid. Aside from this, it has been noted generally that solar mini-grids in Sub-Saharan Africa are not commercially self-sustaining but depend on grants from governments and donor agencies, which is not sustainable (AEE, 2025).

Despite the seemingly high solar energy potential, almost all solar energy mini-grid projects are non-commercially self-sustaining but depend on government and donor agency grants hence they are left unperpetrated while few purely commercially attempts at formative stages with high degree of failure. This is mostly due to the absence of a workable energy model that factors all the technical and economic peculiarities inherent in the region as well as other consideration. This is even so despite the International Energy Agency projecting about that about 150million Africans will access electricity via mini-grids by 2040. While the number of mini-grids grows, the sustainability especially given the nascency of the industry with dearth of prove commercial success remains a big question unanswered. This leaves a huge void of uncertainty in the quest for the realization of reliable quality energy supply for the region (Fajardo et al, 2025; ECA, 2021; Agbo et al, 2024).

As the largest and leading black and African nation, Nigeria is in every bit a microcosm of the of both developing and underdeveloped world especially Sub-Saharan Africa. Hence, any solution that successfully addresses energy poverty in the country will have a positive domino effect in other countries in the same socioeconomic level with Southwest Nigeria being easily the most progressive area to initiate such revolutionary scheme (Statista, 2023).

The perennial poor and epileptic electricity supply in Nigeria worsened by weak political will and massive infrastructural deficit has been the biggest threat to industrial growth, socioeconomic advancement and foreign direct investment due to the many direct and indirect consequence such as insecurity, high cost of local manufacturing, spiralling foreign exchange, and brain drain among other things. (Kolawole, 2023)

Providing sustainable, clean, and affordable locally available renewable energy powered mini-grid has been collectively identified by experts, international financiers, united nations, and technical experts globally as the ultimate solution to tackling energy deficit which is at the core of meeting the objectives of over 80% of the Social Development Goals (SDG). With the high line losses of over 30% being recorded by Nigeria's inefficient and frequently collapsing national grid system especially in the last 15years, it is clearly obvious that energy efficiency has to be developed alongside new power generations capacity which means a partial or complete departure from the existing national load network beginning from unserved and unconnected area via mini and microgrid load network is a necessity (Ikeme and Ebohon, 2005).

Being that solar energy is one of the locally available renewable energy resources in high supply in Southwest Nigeria like in the rest of Sub Sahara Africa, it is necessary to prioritize solar electricity driven mini – grid especially in small network of interconnected microgrids that may be designed in interoperable smart systems for energy efficiency especially in rural settlements, cottage industries, small businesses, value added agriculture, and exclusive urban communities since about 50% of the population reside in rural or remote areas (UN, 2015).

Solar energy can be converted to power by direct (photovoltaic system) or indirect (concentrated solar power) technology, each with its merits and demerits when it comes to cost, efficiency, capacity factor, development issues, technical complexity, and other key influencing decision making parameters. Solar photovoltaic (PV) system is the simplest, flexible, quickest, ubiquitous, and cheapest renewable energy technology yet developed especially for naturally endowed high insolation areas like tropical countries such that individuals even with little or no education can be taught to procure and self – install small units. This makes solar PV ideal for short, medium, and long-term power solution especially in governance areas where policy summersault caused by change of government is rife (Okwori, 2011).

Again, due to the high losses incurred by the national grid, it is important to serve areas not yet connected or who are poorly supplied with networks of solar grids instead of extending the main grid to them as a short-term solution which can be enhanced in the medium and long term. Solar PV grid system has been at the center of Net Zero energy transition policy of the United Nations Framework Convention on Climate Change (UNFCC) to which Nigeria is a signatory and which also forms part of the conditions set out for power project financing by local and international finance institutions, International Donor Agencies (IDA), multilateral corporations, regional development banks, economic blocs, leading energy component original equipment manufacturers (OEM) and so on(IBRD, 2021).

Hence, this study is aimed at seeking solutions to Nigeria's intractable poor power supply problems and ancillary issues, bottom-up through the exploration and exploitation of locally available renewable energy resources with solar PV for grid as a case study, short, medium, and long-term solutions concerning techno–economic viability analysis. Given its median geographical conditions in Sub-Saharan Africa, the Southwest region of Nigeria is being used in this research as a case study. This is to localize the study area for a more specific and deeper study, which can then be replicated in other regions in Sub-Saharan Africa. The model analysis applied for the study is locally and globally applicable, with all differential constraints taken into cognizance (Towoju, 2025).

Objectives

This study, among other things, is planned around the following aims and objectives

1.1.1. Explore solar energy resources, components, technologies, and materials in Sub-Saharan Africa using Southwest Nigeria as a case study

1.1.2. Obtain solar energy data of Southwest, Nigeria for a sufficient number of years

1.1.3. Design a 100kW hypothetical generic flat plate collector solar photovoltaic energy powered mini – grid in multi-source hybrid operable mode

1.1.4. Use techno-economic energy models including TEREVI, TELCOE, HOMER, and MATLAB Simulink to evaluate and determine the commercial viability of the mini-grid system against ultra conservative variables, local constraints, and peculiarities.

2.0. Literature Review

Elegeonye et al (2023) assessed the feasibility of a 85KW solar power system at Gbamu-Gbamu in Ijebu-Ode, Southwest, Nigeria using RETScreen but software and concluded that its is viable. However, this study did not factor in local constraints and peculiarities which have subtly made solar mini-grid projects in Nigeria and Sub-Saharan Africa generally not practically commercially sustainable over the years, thus leaving huge uncertainties.

Agbo et al (2025), used Python for Power Systems Analysis (PYPSA) and other tools to analyse the suitability of renewable energy mini-grids especially solar in addressing rural electrification in Nigeria. However, the study is basically and overview and like most past studies lacks local constraints, and judgement beyond basic technical, economic, and environmental factors. This leaves a whole lot to address both in depth and coverage, especially given the study's scope.

Odetoye et al (2023) carried out a multi-year comparative analysis between a 2MW solar and 200kW hydropower hybrid mini-grid and a diesel mini-grid for a fast-growing commercial community in Nigeria and concluded that the renewable energy min-grid was more cost-effective. However, like other previous researches, this study was limited to just the technical, environmental, and energy assessment without considering local peculiarities and constraints let alone the actual local economic realities cum social factors.

Babalola et al (2021) assessed the socioeconomic impact of off-grid renewable energy on rural community using Gbamu-Gbamu village in Ijebu Ode, Southwest Nigeria by carrying out a survey on over 80 small businesses and measuring the results of employment and income generation. Though the scope of the research did not include commercial self-sustainability of the power system. It did expose a number of hidden social issues and economic realities directly and indirectly that hampers the commercial success of mini-grid beyond being a welfarist project.

Adeleke et al (2016) assessed the causes of massive solar energy systems failure in Nigeria including private and mini-grid projects with average life being 2 to 3years by analysing mini – grid installations projects in Northern and southern Nigeria. The results show serious social, administrative, material, governance, and several ignored issues including systemic culture and material regulations among other often disregarded items in almost all previous researches as being key failure points. Thus, was also partially supported by ESMAP (2017) in the World Bank mini – grid report on Nigeria.

Hence, in all the studies so far, there has not been a techno-economic research based on energy models that factors the social, sustainability, technical, economic, and governance issues among other things for a wholistic evaluation. Hence this study tries to use full proof techno-economic models developed to capture Sub – Saharan peculiarities in order to address or key variables for proper feasibility assessment in order to avoid new projects going the way of the past by either failing within 5years or going off as one-term installations propped by donor funding or government grants.

3.0. Methodology

This study is carried out by an overview of solar photovoltaic energy generation theory and technology, as well as ancillary systems such as battery energy storage (BESS) and other components applicable to the research. This is in order to get a thorough perspective of the multi-layered and sometimes technically complex concepts, components, technologies and materials of solar photovoltaic systems underlying the system design and planning as a critical success factor in real-time development, as mistaken in many failed past projects.

A 21-year daily solar insolation data was obtained from the Langley Research Center (LaRC) satellite measurement and recording of the National Aeronautics and Space Administration (NASA) for 22 locations evenly spread across Southwest, Nigeria, with at least 3 locations for each of the 6 states in the region. Similar information was obtained from the National Renewable Energy Laboratory (NREL) and the Nigerian Meteorological Agency (NIMET). Only the LaRC data was used for the analysis, design, and planning in this research, being the most conservative, consistent, comprehensive, and largest, while the NREL and NIMET solar energy data were only used for comparison and to ensure consistency for data integrity.

The geolocational solar energy data were obtained from sites in the following cities in Southwest Nigeria: Obafemi Owode, Abeokuta, Igboho, Okitipupa, Snake Island, Akoko, Akure, Ibadan, Igbo Ora, Ijero Ekiti, Ikire, Ikorodu, Ila Orangun, Ilesha, Ise Ekiti, Iseyin, Ondo Town, Osogbo, Owo, Shagamu, Lekki

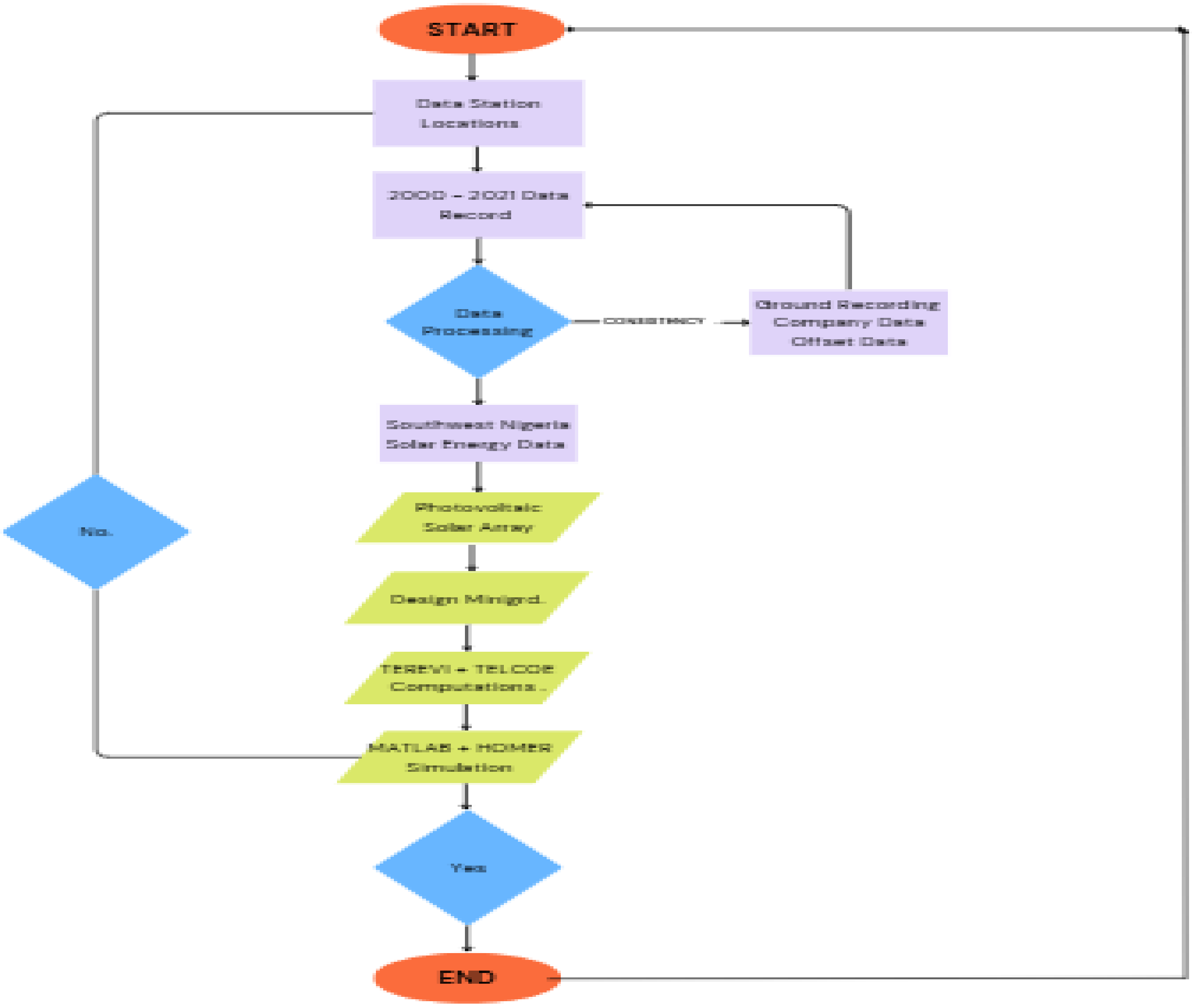

Fig. 3.1: Process flow chart of the solar photovoltaic mini-grid commercial viability study

The 21-year daily insolation was averaged to monthly values, while A 100kW hypothetical generic flat plate solar photovoltaic mini-grid with interoperable and hybrid energy configuration was designed. The mini-grid systems were evaluated using the Techno-Economic Renewable Energy Viability Index (TEREVI) and the Techno-Economic Levelized Cost of Energy (TELCOE) as in Okwori (2025, 2025) to determine the commercial viability. The design was also simulated using MATLAB Simulink and HOMER simulation for the optimized energy cost. Figure 3.1 shows the process flow diagram of the research project.

The schematic of the hybrid energy configured 100kW mini-grid system interoperable with the main grid or other mini-grid concatenation is shown in Figure 3.2. Similarly, the power train is shown in Figure 3.3.

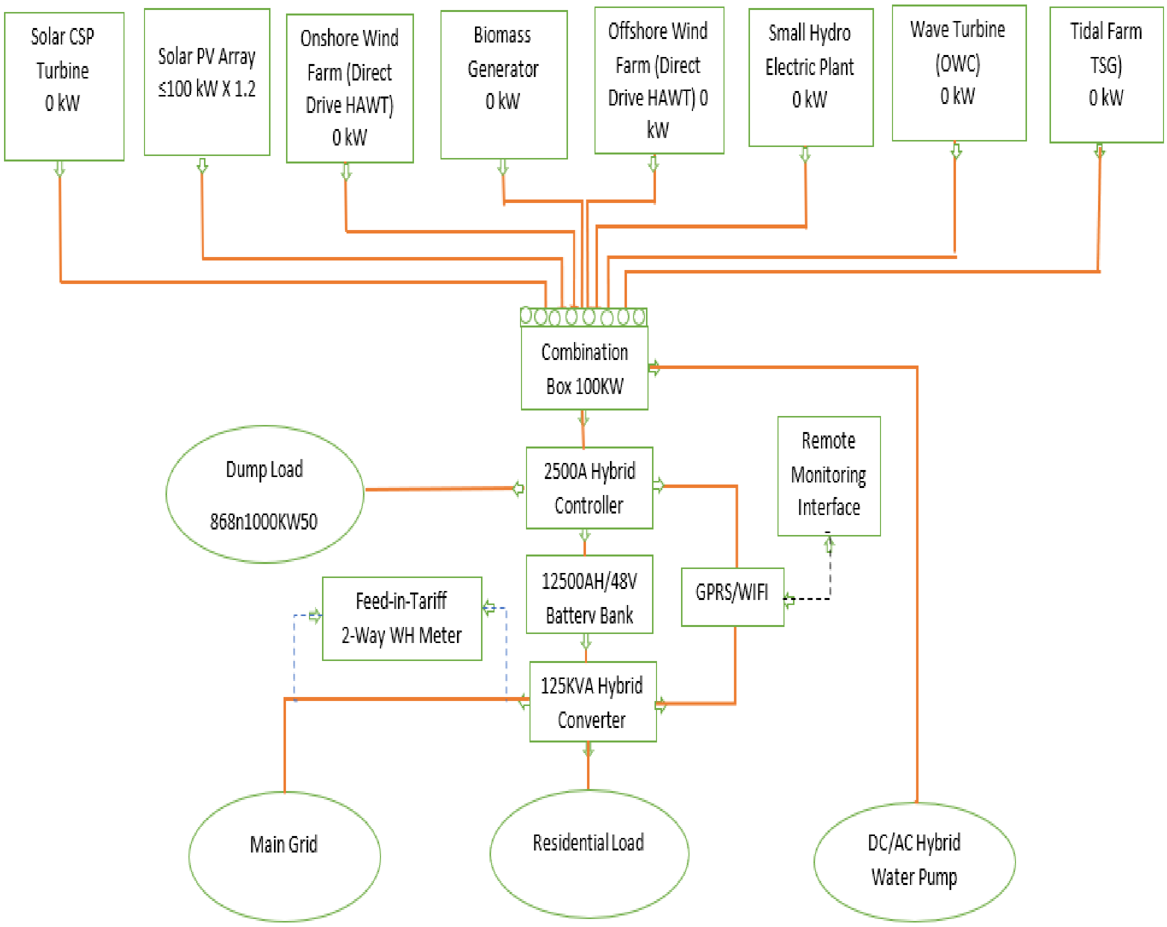

Fig. 3.2: Schematic of the hypothetical 100kW photovoltaic mini-grid in hybrid configuration

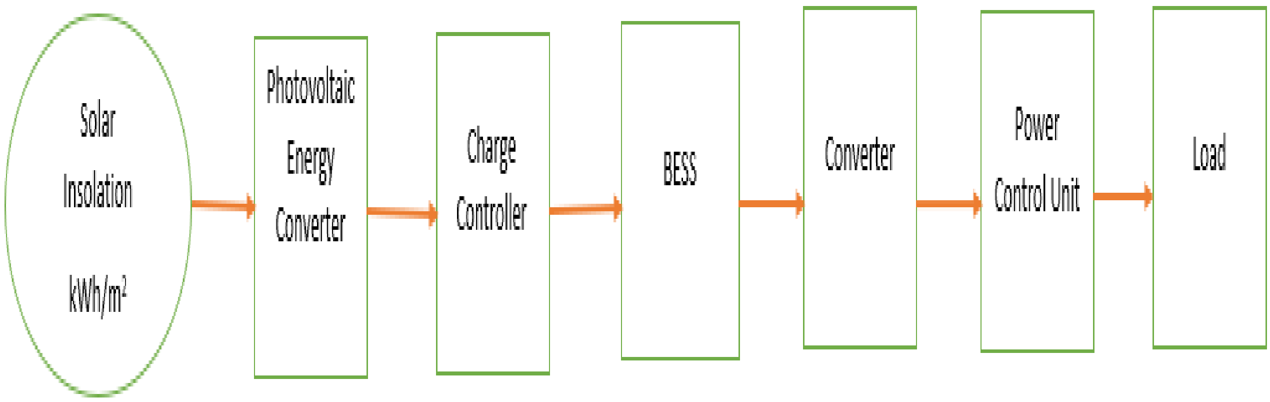

Fig. 3.3: Photovoltaic powertrain of the 100kW mini-grid system

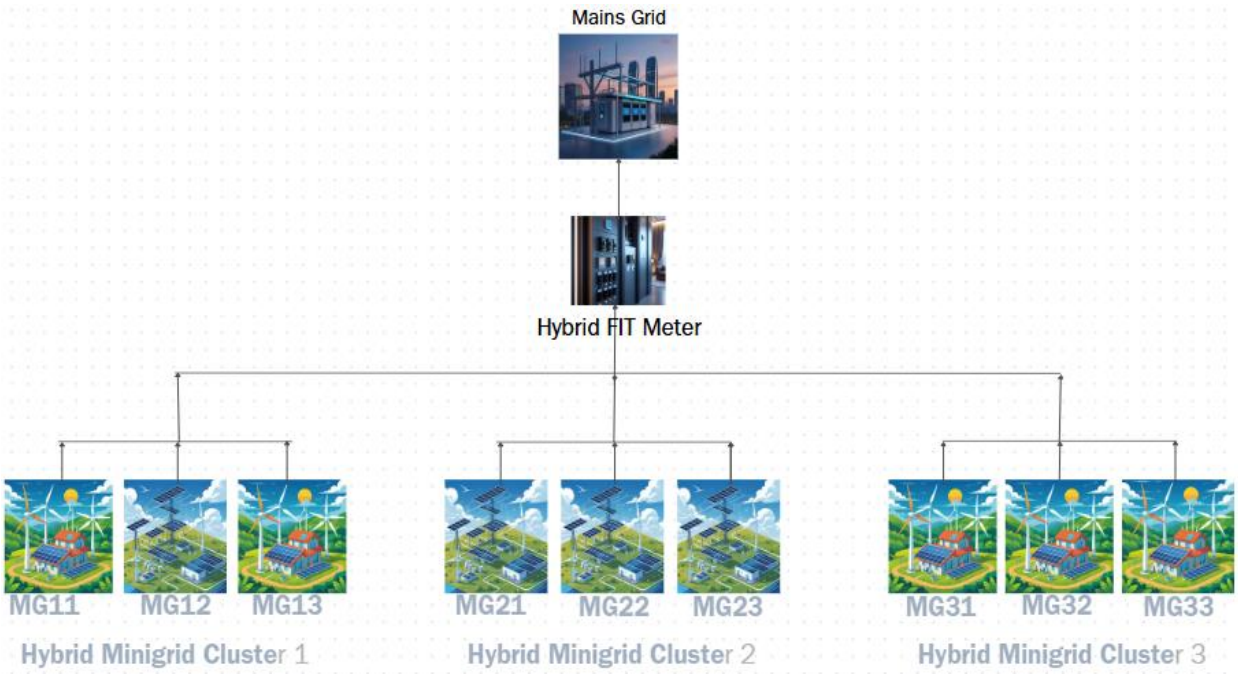

Fig. 3.3: Archetypical scheme of 100kW hybrid mini-grids in concatenated configuration for rural electrification in Sub-Saharan Africa showing a concatenation of mini-grids (MG) in neighboring clusters and interconnected with the main grid. This is based on the bottom-up renewable energy solution strategy for sustainable commercial rural electrification in Sub-Saharan Africa (Okwori, 2025).

3.1. Solar Photovoltaic Power Principles and Technologies

Solar photovoltaic (PV) is a technology for the direct conversion of solar radiation energy into electricity using direct normal radiation (DNI), diffused horizontal irradiance (DHI) and reflected solar radiation on the earth's surface called solar insolation or solar irradiation.

Nigeria's solar energy potential is so high that just 1% of its 923,768Km^2 landmass is worth an energy value of 270,000GWh/year or 1,428,000MW in power generation using 15% efficiency solar PV modules (CRET, 2015) given its average solar insolation of between 3.5Kwh/m^2 and 7.0KWh/m^2(Akuru and Okoro, 2010)

The sun is a thermonuclear reactor based on the fusion of hydrogen molecules under the high heat of 6000◦C at the surface to 15,000,000◦C at the core and pressure of about 2.5 X 10^{11}atm which not even any refractory material known to man can withstand and at which even the hardest metals and diamond will be vaporized. The average annual value of solar radiation incident on the earth's atmosphere is 1367W/m^2 of which only a maximum of about 40% reaches the earth's surface which in turn varies with locations (Planet Facts, 2022).

Total Solar Irradiance (TSI) is the sum of solar radiation of all wavelengths reaching the earth's upper atmosphere in W/m^2 while Direct Normal Radiation (DNI) is the perpendicularly incident solar radiation measured on the earth's surface in W/m^2.

Global Tilted Irradiance is the total solar radiation incident on a surface with a given tilt and azimuth angle while Global Normal Radiation (GNI) is the solar radiation incident perpendicularly on a horizontal surface of the earth in W/m^2.

Global Horizontal Irradiation (GHI) is the sum total of solar radiation on a surface with respect to its tilt and azimuth angle in W/m^2. Hence, given the solar zenith angle to be Ψ at a given installation, the GHI is given thus:

$GHI = DHI + DNICos\Psi$ ………3.1

Solar constant (I_C) is the value of solar energy radiated perpendicularly on a horizontal surface of the earth outside its atmosphere at its mean distance from the sun, which is estimated at 1.367KW/m2 (Coddington et al, 2016).

Solar irradiation is electromagnetic radiation with mixture of different wavelength, both visible(sunlight) and invisible (infra-red and ultraviolet wave) of which 99% of the total energy lies within wavelength of 0.15μm to 4μm. Visible light or sunlight makes up only about 42.3% of solar radiation while infrared and ultraviolet radiation make up 49.4% and 8% respectively.

Direct radiation is non – divergent electromagnetic radiation from the sun to the earth's surface and are the most important solar radiation for electricity generation by photovoltaic cells. Diffused solar radiation are electromagnetic radiations from the sun deflected by encountering particles of dust and cloud or other solid elements on its way while reflected radiation are electromagnetic radiations reflected by objects on the earth's surface. All the different types of radiation contribute in different proportion to the overall solar energy received on a surface depending on location, weather condition, and structures or topography.

Ultraviolet radiation is the most powerful and dangerous of the different types of radiation having the shortest wavelength by which it is divided into 3 groups: UV-A, with wavelength of 300nm to 400nm; UV – B, with wavelength of 280nm – 320nm; and UV – C, with 100nm to 280nm respectively. The shorter the wavelength the more intense and dangerous but fortunately UV – C being the most damaging to the ozone layer and human skin makes up just 0.5% though UV-B and UV-C still penetrate the earth's atmosphere with their respective consequences on the ecosystem.

Infrared electromagnetic radiation however is the primary source of global atmospheric warming especially via water and carbon dioxide absorption of the radiation and subsequent conversion into heat.

Solar insolation(I), also referred to as solar flux density, is the amount of solar energy falling on a horizontal surface of a given location of the earth in W/m^2 and varies across the globe with regions along the equator having higher values and regions in the poles having the least values since the earth is not perfectly spherical and owing to the earth's rotation(movement about its own axis) and revolution(movement round the sun).

Given the solar zenith angle, Ψ with distance and mean distance between the earth and the sun as S and S_m, for $Cos\Psi > 0$ and $Cos\Psi \leq 0$. then the Insolation is given by:

$I = I_C \frac{{S_m}^2}{S^2} Cos\Psi$ ……………3.2

Given a spherical triangle with radial side lengths P, Q, R, and given γ to be the spherical angle of the vertex opposite side length R with respect to a given observer latitude λ and longitude Ø with respect to the hour angle φ, and declination δ with azimuth angle **α** and horizontal angle **β**, applying the Trigonometric Law of Cosine based on a review of ITACA, 2023, we get:

$CosR = CosPCosQ + SinPSinQCosR$ ……………3.3

From which we obtain:

$Cos\Psi = Sin\lambda Sin\delta Cos\beta + Sin\delta Cos\lambda Sin\beta Cos\alpha + Cos\lambda Cos\delta Cos\beta Cos\varphi - Cos\delta Sin\lambda Sin\beta Cos\alpha Cos\varphi - Cos\delta Sin\beta Sin\alpha Sin\,\varphi$ …...2.4

Or simply as:

$Cos\Psi = Sin\lambda Sin\delta + Cos\lambda Cos\delta Cos\,\varphi$ ………..3.4

Given that:

$$\gamma = \varphi$$

$$Q = \Psi$$

$P = \frac{1}{2}\pi - \lambda$ 3.5

$Q = \frac{1}{2}\pi - \delta$ 3.6

The daily insolation (I_D) is considered to be the average of one full rotation of the earth about its axis from φ = π to φ = -π:

$I_D = -\frac{1}{2\pi}\int_{-\pi}^{\pi} Id\varphi$ 3.7

Given φ_0 at positive I; that is at sunrise wherein $\varphi = \frac{\pi}{2}$ then:

$Sin\lambda Sin\delta + Cos\lambda Cos\delta Cos\ \varphi_0 = 0$ 3.8

Or

$Cos\ \varphi_0 = -\ Tan\ \lambda Tan\delta$ 3.9

Note that: For sunrise, tan(φ)tan(δ) > 1, which is at $\varphi_0 = \pi$, therefore there is insolation.

For sunset, tan(φ)tan(δ) < −1, which at $\varphi_0 = -\pi$ therefore there is no insolation, I = 0

Because $\frac{S_m{}^2}{S^2}$ value remains constant throughout the day and

$\int_{\pi}^{-\pi} Id\varphi = \int_{\varphi_0}^{-\varphi_0} Id\varphi$ 3.10

Then

$I = I_C \frac{S_m{}^2}{S^2}\int_{\varphi_0}^{-\varphi_0} Cos\psi d\varphi$ 3.11

$I = -2I_C \frac{S_m{}^2}{S^2}\lfloor \varphi_0 Sin\lambda Sin\delta + Cos\lambda Cos\delta Sin\ \varphi_0 \rfloor$ 3.12

Hence:

$I = \frac{I_C}{\pi}\frac{S_m{}^2}{S^2}\lfloor \varphi_0 Sin\lambda Sin\delta + Cos\lambda Cos\delta Sin\ \varphi_0 \rfloor$ 3.13

Given module obliquity as V and taking ω as the polar angle with value of zero at vernal equinox, we have

$\delta = Vsin\omega$ 3.14

For axial tilt:

$Sin\delta = SinVSin\omega$ 3.15

Taking τ as the conventional perihelion longitude and e as the vernal equinox based on Glen, 2012:

$S = \frac{S_m}{1+eCos(\omega - \tau)}$ 3.16

$\frac{S_m}{S} = 1 + eCos(\omega - \tau)$ 3.17

If n is the day number of a specific day in a year numbered from 1st January to 31st December, knowing that $\omega = 0°$ at vernal equinox, $\omega = 90°$ at summer solstice, $\omega = 180°$ at autumnal equinox and $\omega = 270°$ is at winter solstice and taking the astronomic values of e, ω, and τ we have the daily insolation equation may then be reduced thus (ITACA, 2018):

$I_D = I_C\left[1 + 0.034Cos\left(\frac{2\pi n}{365.25}\right)\right]$ 3.18

The above equation serves as the basis for estimating year-round solar energy generation based on a panel module. This estimation takes into account that solar insolation varies with geographical locations and changes daily and seasonally throughout any given year, as well as considering unforeseen natural occurrences.

Since the performances of solar technologies vary widely with component, material types, manufacturing process and installation methods as well as designs and optimization strategies, it is import to adequately access the various option for proper procurement and best value for money in meeting the mini – grid goals and ensuring attractive black bottomline of the project's investment.

3.2. Components and Materials of a solar PV system:

For a practical perspective, it is important to look into the components and materials of photovoltaic power systems as part of the guides on effective and sustainable design and installation

3.2.1. PV Module:

PV module or panel is a combination of solar cells which are groups or layers in designs of 2 or 4 – junction semiconductor cells which could be of n – p – n (N–Type) or p – n – p (P – Type) in a thin film(also called a wafer) configuration upon which the striking of sunlight sets up electric field by the movement of charges which increases with the intensity of the radiation (direct or indirect) up to optimal levels for the material and technology.

Most PV in the market today have efficiencies of 15% to 25% and are of amorphous (thin film) silicon, monocrystalline and polycrystalline make made from glass sheet, metallic frame bus wires and standard 12V wires. The solar cells are fused by soldering together in a matrix between glass panels by which electric charge is generated upon sunlight falling on them. The metallic frame protects the panel against hostile atmospheric conditions and as enables proper mounting and needed structural rigidity by holding the glass sheet and other components together.

The glass sheet serves as protection for the semiconductor cells by preventing direct contact between the cells and the atmosphere. In addition, the glass sheet under its exterior contains a protective and insulating casing to minimized humidity and heat dissipation in the panel that could result in lower PV efficiencies, which is a core aim of manufacturers to ensure light is captured without panel suffering overheating. The wires help to regulate the flow of charge from the PV to the inverter for a sustainable and efficient PV system while the bus wires connect semiconductor solar cells in parallel. The cells are the main component of the panel itself.

The semiconductor could be pure silicon or doped with boron, gallium or telluride to form the silicon ingot by which the addition of phosphorus enables the cell to conduct electricity. The silicon ingot is thereafter cut in thin sheets or slits and coated with an anti-reflective material film which is then sliced into slits to streamline the flow of electricity in the panel. A P-Type cell is positively charged by virtue of its boron base whereas an N-type cell is negatively charged by virtue of its phosphorous base. Though N-Type cells are more efficient due to higher solar energy trapping and conversion rate, they tend to deteriorate much quicker than P – Type cells when exposed to very bright sunlight or hotter environments, especially as obtained in the tropics or hot summers.

PV modules generate DC and may operate with direct or indirect radiation, which means there can still be output even in cloudy weather but there is an upper limit of radiation beyond which panel efficiency starts dropping depending on its technology of built, material, and design. There are several solar PV technologies that vary in their efficiencies well over 100% depending on design and material as well as shapes and dimensions of which polycrystalline and monocrystalline are the most popular in the market.

Though monocrystalline is superior in technology to polycrystalline and amorphous (thin film) PV modules, there are more premium PV technologies limited by high-cost factors such as high purity silicon type, multi bus bar (MBB) type, Heterojunction, cells (HJT) and passivation (PERC) type. Monocrystalline modules are manufactured by being cut from a single large block of pure semiconductor(silicon) in a wafer matrix format as individual units to be attached to form a panel which takes higher man-hours to produce due to higher precision with more tasteful aesthetics which are typically shiny black but may be designed with a variant color thus consequently more expensive.

Polycrystalline PV modules are made of the same semiconductor(silicon) as polycrystalline but are manufactured by cutting as silicon wafers from multiple fragments or crystals of different silicon melted and refused together before being joined to form panels. Monocrystalline PVs typically have bluish tan appearance and are performance-wise superior to amorphous panels but less efficient than monocrystalline which makes them less expensive than the latter.

Amorphous PV modules are typically made of any of such materials as Cadmium – Telluride (CdTe), Copper – Indium Gallium Selenide (GIGS) or Silicon (a-Si). Thus thin – film PVs are made of lower material quality compared to crystalline PV technologies which gives them considerably lower efficiencies and also lack the structural toughness to be installed on rooftops though much cheaper (Zito et al, 2023). The thin film PV module is amorphous and thus non – crystalline and is therefore embedded in glass, plastic or metal substrate, which makes it thin with greater structural flexibilities that also enables it to be foldable(bendable), light weight, thin and fit for more versatile installation but are however less efficient than monocrystalline or polycrystalline. Each type of thin-film solar panel is less expensive than both crystalline panels but is also less efficient. Hence an application that might be structurally or space-wise difficult for crystalline panels may fit for thin film PV rather than nothing.

In all the various PV technologies, manufacturing is complete by fitting the PV unit in a glass metallic frame for protection from physical objects and inclement atmospheric conditions. The performance of PV modules also depends on a number of external factors such as the installation location's irradiance (W/m^2) and latitude, time of the day, season, windspeed, atmospheric rarefication, shading, panel orientation, temperature, dirt, and dust (Zito, 2022).

The power rating of PV modules in Watts(W) is conducted on Standard Test Conditions (STC) (Zito et al, 2023) simulated at 1000W/m2 insolation and 25◦C with an airmass of 1.5g, though in tropical locations temperatures could climb up to over 100% of the STC measures in some areas and at most times (Kuchta, 2022). During full sunlight, internal cell temperatures could be up to 20 to 30 higher than ambient temperatures causing an 8 to 12% loss of PV power generation which conversely indicates higher cell efficiencies at lower temperatures that vary with technology and temperature coefficient.

Power Temperature Coefficient (%/◦C) is a measure of the efficient increase or decrease per temperature rise or fall above or below STC temperature value (25◦) by which HTJ, IBC monocrystalline and polycrystalline technologies have PTC of 0.25%/◦C, 0.30◦C, 0.38%/◦C, and 0.40%/◦C respectively. The lower the PTC of a PV module, the better (Kuchta, 2022).

Also, Thermal Cycling Test (TCT) are conducted on solar PV panels in order to test its ability to withstand extreme temperatures or the temperature conditions of its proposed installation site by measuring its degree of expansion and contraction under given temperature ranges. Thus, PV modules are capable of generating electricity well over their nameplate capacities in cold sunny weather conditions. The efficiency of a PV module is measured by the Fill Factor (FF) which is determined as the ratio of input radiation energy to output power at optimum current and voltage

The number of solar PV to be installed to make up a solar array is determined by the unit capacity of each module, area of land, string size, and required installation capacity. Panels come in different efficiency depending on technology and original equipment manufacturer (OEM). A string is a number of PV modules connected in series. The output voltage, resistance, voltage drop, and charging rate are determined by the type of connection (parallel, series, or hybrid), strings, required load, storage, inverter, power management, system (if any), and controller capacities among other things. PV module efficiency is calculated by the ratio of rated power to panel area (Zito et al, 2023) though larger panels designed with larger cell sizes have proven more efficient due to increased surface areas. Commercial PV modules typically have 72 cells while residential modules typically have 60 cells $156mm^2$ panels

3.2.2. Charge controller:

also called battery regulator, a charge controller is a device that is designed to limit the rate of charging and discharging of a battery and thus preserves battery life and protects against overvoltage and associated safety risks. The charge controller is a primary component of solar PV systems and a key determinant of safety, battery life, quality of electricity generation and system efficiency. Charge controllers are optimally sized with respect to battery storage capacity and come in different technologies which also indicate their performance levels such as the, Pulse Width Modulator (PWM), Maximum Power Point Tracker (MPPT), shunt regulator and series regulator.

The shunt controllers are also referred to as pulse regulator because operates by shutting or short-circuiting the PV array once the battery charging voltage reaches the preset level and automatically reconnects when the voltage drops below the preset value due to discharge. Thus, shunt controllers typically comprise transistors(relay) for short – circuiting the PV and blocking diodes for preventing the shorting of the battery in the process. Thus, this technology is basically limited to negative grounded system since the blocking diode is located on the positive line.

Series controller system is an on/off technology similar to shunt regulators and uses transistors or relays on negative or positive ground to open–circuit (or disconnect) the PV array upon battery attaining the preset voltage level and reconnecting once the voltage drops below set value. The series controller's array voltage is set to be slightly higher than the battery voltage in manner as being the sum of battery voltage and voltage drop across relay/resistor, as the reverse indicates problem.

Series controllers are a step more advanced than shunt due to the fact that they are capable of having multiple relays and transistors to activate multiple voltage disconnect and reconnects set points thereby ensuring more step adjustments for better performance which effectively makes it's a multi – stage a voltage charge regulator which enables it to run much cooler especially with relay connector/disconnector thus making it better suited for commercial scale projects. PWMs are similar to in operation but more advanced than series controllers by using transistors rather than relays to switch on/off the PV array with optimized self–adjusting varying pulse widths and speeds, high frequencies. PWMs are basically ahead of the series technology owing to multiple adjustable self-regulating positions (width) of the transistor and can also be on positive or negative lines and ground.

MPPT technology is a step ahead of PWM controller by being able to vary the PV voltage by choosing the maximum voltage point and converting it to a suitable value required by the battery by first converting the PV input DC to high frequency AC and then reconverting to a suitable DC voltage to be fed to the battery. MPPT uses the negative line as a reference and switches to the positive line. By this process, a 100% transistor width indicates closed circuit which allows the battery to be full charged from zero to 100% State of Charge (SOC) while 0% width indicated full charging position or open circuit in which charge flow into the battery is stopped having attained full voltage controllers being essentially series controllers, often come with designs that have provision for conversion to either series or shunt controller in order to suit loads that are sensitive to the high-frequency noise and harmonic emission of PWM.

3.2.3. Converter:

an inverter circuit converts direct current (DC) electricity to alternating (DC) electricity to alternating current (AC) electricity, typically with power factors of about 0.98, which makes their losses negligibly minimal. The inverter is a device installed with its DC port linking the PV or battery storage, while its AC port supplies the consumer through the miniature circuit breaker (MCB).

The inverter is a necessary component of a solar PV system because direct solar electricity generation is DC while most user equipment like television, refrigerators, fans, lighting, etc. are AC-fed. Sometimes, the inverter is integrated with a charge control and storage system, especially for small applications for more compactness, simplicity of construction easy transportation, and reduced encumbrances.

3.2.4. Battery Energy Storage System (BESS):

A battery is by definition a group of electrochemical cells for accumulating electrical energy in form chemical energy for future use. Batteries for solar PV system application come in various technologies and performance with respect to OEM and material superiority.

Popular technology available battery technologies include Lead Acid Accumulators, Nickel – Cadmium, Lithium – Ion and Tubular. A key consideration in determining battery choice is chargeability, allowable depth of discharge, efficiency and durability which all together determine cost and usage choice.

Battery lifespan could by nameplate be up to 15years but actually typically about 10years with discharge pattern and ambient conditions being the major determinant of durability thereon. At an optimal ambient temperature range of 20◦C to 25◦C, batteries will last up to 10years or about their design life but with higher temperature say +10◦C, the lifespan could drop by up to 50%. This why battery maintenance is much higher in the tropics by virtue of the need to ensure proper ventilation and good ambient conditions.

State of Charge (SOC) is the level of charge accumulated or while Depth of Discharge (DOD) is the amount of charge left in a battery after undergoing or while undergoing discharge. Frequent DOD below 50% reduces a battery's life hence it is good to size storage with DOD not below 50%. Lead – Acid Accumulator is the most popular and oldest in PV usage and have efficiency of up to 90% of which Valve Regulated Lead Acid (VRLA) Absorption Glass Mat (AGM) battery is the most advanced with good life/price ratio. (Planas, 2021).

Lead – Acid batteries are commercially available in either flooded or seal type. They are very reliable, technically familiar, easy to recycle or regenerate, relatively cheap and easy to dispose. However, lead – acid accumulators tend to have shorter average lifecycles of 8+/-3years (Lane, 2021) due to low DOD which also means more frequent charging. Also, the flooded types need regular topping of electrolyte with distilled water. Thus, lead–acid deep cycle controllers tend to be more suitable for residential and microgrid as well as emergency backup uses rather than for commercial scale projects with virtually all battery OEM having the technology in their series stock.

Nickel – Cadmium Batteries are very favoured for they high durability and ability to withstand extreme ambient temperatures and physical conditions aside being virtually maintenance free aside being safer on fire issues and needing no technically complex optimization scheme. Because they are highly toxic, have memory effects (loosing charges easily) and hard to dispose or recycle, they are considered not environmentally friendly and highly limited in use or outrightly forbidden in a number of jurisdictions. Nickel – Cadmium batteries are most preferred in large utility storage and installations typically offsite and on outdoor facilities like telecoms and commercial sized mini – grids

Lithium – Ion batteries are fast gaining more ground in markets due to their high energy density and efficiency resulting in less bulkiness as well as longer lives often with over 8+years warrantees (Lane, 2021) aside their ability to withstand less clement environments and operating conditions coupled with higher DOD meaning longer use and extremely low maintenance thus giving it reduced cost of operation. Their higher endurance and high DOD make them very favoured by electric vehicle (EV) OEMs and application for more difficult environments such as limited spaces, confined or exposed locations. They are also used in residences.

However, the thermochemistry of lithium–ion batteries has high thermal runaway, which is a major safety risk that could result in fire or explosion, aside from the fact that they are extremely expensive. Tubular Batteries are designed with vertical tubes juxtaposed in a honeycomb–like matrix for improved current flows and to slow down corrosion of their materials compared to grid-like flat plate designs. Tubular batteries are reliable, durable, space compactable (choose tall or short), resilient, and quite tolerant of hostile environmental conditions, which makes them fit for more power-grabbing appliances, tougher operational demands, and long discharge accompanies with low maintenance.

Tubular batteries could be tall, short, or type and have a fairly average lifespan of about 6years for short and 9years for long type. However, the short tubulars tend to range in capacity below 200AH, while the tall tubulars could have higher capacities and are taller and thinner. The tall tubular batteries are very efficient and have the all-around performance superiority over the short except that they take up more space, thus limiting their use for residences. Tubular batteries are highly favoured for use in UPS, inverters, and various mobile and stationary machines due to their being compact, efficient, and high power-to-space ratio, among other things.

A flow battery is an emerging technology that uses water-based electrolytes in the partitioned compartment between the positive and negative terminals, which makes them larger in size construction owing to lower energy density. They are extremely safe and non–toxic with almost zero thermal runaway risk and also have the longest durability of battery technologies well over 20 years, aside from being extremely low maintenance and allowing for 100% discharge without consequence, among other things (Lane, 2021). Due to their thermochemistry, they are of relatively low energy density and thus have to be bulky in construction, thus taking up more space and consequently being quite expensive. Thus, flow batteries are more favoured for commercial-scale projects and less suitable for residential uses or EV applications. However, being a technology still pretty much under development, flow batteries are expected to improve in terms of charge-to-size ratio and cost shortly, which will make it the preferred option for most applications.

Lead-acid accumulator wet cells are of either open or sealed type. The open type allows the electrolyte cover to be opened for electrolyte topping or replacement, while the sealed type is closed by having valves that open for gas to escape in the case of high load, liberating excessive gas during operation.

3.2.5. Solar Tracker:

Solar tracker is an adjustable joint that could be either electromechanically or manually operated for changing the direction of PV plates to all face the sun in order to optimize radiation from sunrise to sunset. Solar trackers could be automatically operated electromechanically or simply by manual operation and could be uni-axial, poly-axial, or of a universal joint in an adjustable direction, which also determines the ability to focus more optimally on sunlight, of which a universal joint is the best. Mechanical trackers are not reliable and require manpower to periodically adjust the plate direction, while the automated electromechanical type is most reliable, though it takes some of its energy to operate.

3.2.6. Generation meter:

an indicator module for qualitative and quantitative measurement of electricity generation by the PV system, which usually includes a coloured(red) light flashing. The brighter the sun radiation, the faster the red-light flashes once it's generating electricity.

3.2.7. Cabling and connectors:

these include all forms of conductors such as wires, cables, and busbar as well as ancillary components for linking components and transmitting generated electricity to the load.

3.2.8. Export limiters:

a device designed to cap or completely prevent export of electricity from a mini–grid to the main grid or an external grid system as a result of which it is preset to limit, regulate or stop load export to external loads or grids. This is so because, for technical or commercial reasons, an interconnected local Electricity Distribution Company (DISCO) to which the mini–grid exports excess power generation may not be in a position to accept such electricity from time to time. Though not a primary component of solar PV systems, Export Limiter is a necessary component for installation, especially for mains interoperable mini–grids or microgrid catenation as a power management strategy for managing both technical, safety and commercial interface.

3.2.9. Energy monitoring:

monitoring, measurement, verification, and recording or reporting of system operation.

3.2.10. FIT Meter:

Feed in Tariff of smart meter 2–way meter is used for interoperable mini–grid connections to meter the volume and monetary value in electricity export and import between a mini–grid and the larger or other grids connected to it. This allows for financial settlement in the export of excess electricity generation or in imports to make up for shortfalls.

4.0. Results

The 21 years (2000 – 2021) solar insolation for dates for 23 cities and the Bight of Benin Southwest Nigeria coast, as shown in Tables 4.1 and 4.2, were acquired from NASA's LaRC Earth Data. To ensure conservative corroboration with ground data obtained from NIMET, as well as the NREL, other satellite-based sources like Surf-forecast.com, among other limited and isolated data from private and corporate sources for the given locations at different periods in time and duration. Tables 4.3 and 4.4 show the exergy of solar photovoltaic generation technology based on 20% module conversion efficiencies.

AVERAGE ALLSKY SOLAR INSOLATION (KWH/M2/DAY) FOR STRATEGIC LOCATIONS ACROSS SOUTH-WEST NIGERIA 2000 – 2021													
LOCATION	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	MEAN
OBAFEMI OWODE	4.90	4.78	4.95	5.02	4.70	3.97	3.89	4.12	4.18	4.67	5.06	4.96	4.60
ABEOKUTA	4.93	4.83	4.98	5.10	4.94	4.43	3.87	3.58	4.06	4.70	5.05	4.93	4.61
ADO EKITI	5.08	4.88	5.00	5.05	4.99	4.54	4.10	3.83	4.22	4.73	5.18	5.09	4.72
IGBOHO	5.20	5.27	5.47	5.49	5.26	4.76	4.08	3.75	4.32	4.86	5.29	5.22	4.91
OKITIPUPA	4.85	4.72	4.88	4.90	4.72	4.12	3.70	3.80	3.95	4.54	5.04	4.93	4.51
SNAKE ISLAND	4.90	4.78	4.95	5.02	4.70	3.97	3.89	4.12	4.18	4.67	5.06	4.96	4.60
AKOKO	5.08	4.88	5.00	5.05	4.99	4.54	4.10	3.83	4.22	4.73	5.18	5.09	4.72
AKURE	5.08	4.88	5.00	5.05	4.99	4.54	4.10	3.83	4.22	4.73	5.18	5.09	4.72
IBADAN	4.93	4.83	4.98	5.10	4.94	4.43	3.87	3.58	4.06	4.70	5.05	4.93	4.61
IGBO ORA	4.93	4.83	4.98	5.10	4.94	4.43	3.87	3.58	4.06	4.70	5.05	4.93	4.61
IJERO EKITI	5.08	4.88	5.00	5.05	4.99	4.54	4.10	3.83	4.22	4.73	5.18	5.09	4.72
IKIRE	4.92	4.82	4.98	5.01	4.89	4.41	3.80	3.52	4.01	4.58	5.09	4.98	4.59
IKORODU	4.90	4.78	4.95	5.02	4.70	3.97	3.89	4.12	4.18	4.67	5.06	4.96	4.60
ILA ORANGUN	5.22	5.28	5.54	5.55	5.29	4.84	4.31	3.98	4.47	5.01	5.46	5.25	5.02

ILESHA	4.92	4.82	4.98	5.01	4.89	4.41	3.80	3.52	4.01	4.58	5.09	4.98	4.59
ISE EKITI	5.08	4.88	5.00	5.05	4.99	4.54	4.10	3.83	4.22	4.73	5.18	5.09	4.72
ISEYIN	4.93	4.83	4.98	5.10	4.94	4.43	3.87	3.58	4.06	4.70	5.05	4.93	4.61
ONDO TOWN	4.92	4.82	4.98	5.01	4.89	4.41	3.80	3.52	4.01	4.58	5.09	4.98	4.59
OSOGBO	4.92	4.82	4.98	5.01	4.89	4.41	3.80	3.52	4.01	4.58	5.09	4.98	4.59
OWO	5.08	4.88	5.00	5.05	4.99	4.54	4.10	3.83	4.22	4.73	5.18	5.09	4.72
SHAGAMU	4.90	4.78	4.95	5.02	4.70	3.97	3.89	4.12	4.18	4.67	5.06	4.96	4.60
LEKKI	4.90	4.78	4.95	5.02	4.70	3.97	3.89	4.12	4.18	4.67	5.06	4.96	4.60
MEAN	4.99	4.86	5.02	5.08	4.91	4.37	3.95	3.79	4.15	4.69	5.12	5.02	4.66

Table 4.1: Solar irradiation information of Southwest, Nigeria from 2000 to 2021

AVERAGE ALLSKY SOLAR INSOLATION AT BIGHT OF BENIN SOUTH-WEST NIGERIAN COAST 2000 - 2021												
TIME	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
2000	5.12	5.89	5.77	4.89	4.72	3.54	3.66	3.41	3.5	4.28	5.36	5.07
2001	4.75	4.48	5.14	4.93	4.66	3.75	3.91	4.01	4.42	5.05	5.32	4.93
2002	4.67	4.75	4.78	4.63	4.73	3.49	3.34	3.86	4.39	4.28	4.85	4.92
2003	4.83	5.07	4.47	4.91	4.71	3.37	4.57	4.48	4.02	4.85	4.95	4.73
2004	4.48	4.74	4.41	4.7	4.07	3.82	3.14	4.13	4.47	4.68	5.14	4.88
2005	4.61	4.68	4.78	4.58	4.53	3.27	3.41	4.65	4.57	4.74	5.3	4.8
2006	4.85	4.62	4.8	5.38	4.01	4.4	3.19	3.9	3.62	4.62	5.13	4.85
2007	4.98	4.72	4.74	4.82	4.53	3.34	4.03	4.41	3.85	4.43	4.92	4.88
2008	4.67	4.73	5.04	4.53	4.51	3.99	3.94	4.38	4.35	5.1	5.07	4.69
2009	4.79	4.92	4.81	4.91	4.86	3.89	3.24	3.79	4.35	4.15	5.13	5.23
2010	4.93	5.28	4.62	5.08	4.51	3.64	4.04	3.92	3.83	4.15	5.16	5.02
2011	4.97	4.77	5.23	4.65	4.41	2.92	2.74	3.99	4.39	4.32	5.26	5
2012	4.6	4.34	4.89	4.84	4.38	3.28	3.84	4.69	4.44	4.32	4.8	4.96
2013	4.76	4.63	5.21	5.13	4.43	3.47	3.34	4.43	4.14	4.87	5.02	4.6
2014	4.74	4.25	4.92	4.95	4.61	3.64	3.51	4.06	3.94	4.43	4.99	4.84

2015	4.9	4.59	4.5	5.15	4.59	3.34	3.51	3.86	3.58	4.78	5.26	4.94
2016	4.78	4.36	4.53	5.01	4.48	3.62	3.67	4.19	4.04	4.82	5.11	4.73
2017	4.76	4.5	4.98	5.1	4.69	3.23	3.37	3.59	4.28	4.5	4.96	4.52
2018	4.89	4.18	4.99	4.78	4.52	3.64	3.4	4.18	4.11	4.58	4.92	4.77
2019	4.57	4.18	4.97	4.98	4.25	3.63	3.39	4.24	3.54	3.7	5.06	4.99
2020	5.17	4.65	4.68	5.03	4.71	3.64	3.37	5.11	4.13	4.65	4.91	5.06
2021	4.71	4.39	4.21	5.17	4.87	3.92	4.24	3.89	4.01	4.7	5.25	4.68
MEAN	4.797	4.669	4.84	4.916	4.535	3.583	3.584	4.144	4.09	4.5455	5.085	4.868

Table 4.2: Solar energy data at the Atlantic coast of Southwest, Nigeria from 2000 to 2001

LOCATION	MEAN INSOLATION (Kwh/m2)	C. F	PANEL OUTPUT ENERGY(Kwh/m2)	P F	OUTPUT ENERGY(Kwh/m2)
OBAFEMI OWODE	4.6	0.21	0.966	0.9	0.8694
ABEOKUTA	4.61	0.21	0.9681	0.9	0.87129
ADO EKITI	4.72	0.21	0.9912	0.9	0.89208
IGBOHO	4.91	0.21	1.0311	0.9	0.92799
OKITIPUPA	4.51	0.21	0.9471	0.9	0.85239
SNAKE ISLAND	4.6	0.21	0.966	0.9	0.8694
AKOKO	4.72	0.21	0.9912	0.9	0.89208
AKURE	4.72	0.21	0.9912	0.9	0.89208
IBADAN	4.61	0.21	0.9681	0.9	0.87129
IGBO ORA	4.61	0.21	0.9681	0.9	0.87129
IJERO EKITI	4.72	0.21	0.9912	0.9	0.89208
IKIRE	4.59	0.21	0.9639	0.9	0.86751
IKORODU	4.6	0.21	0.966	0.9	0.8694

ILA ORANGUN	5.02	0.21	1.0542	0.9	0.94878
ILESHA	4.59	0.21	0.9639	0.9	0.86751
ISE EKITI	4.72	0.21	0.9912	0.9	0.89208
ISEYIN	4.61	0.21	0.9681	0.9	0.87129
ONDO TOWN	4.59	0.21	0.9639	0.9	0.86751
OSOGBO	4.59	0.21	0.9639	0.9	0.86751
OWO	4.72	0.21	0.9912	0.9	0.89208
SHAGAMU	4.6	0.21	0.966	0.9	0.8694
LEKKI	4.6	0.21	0.966	0.9	0.8694
MEAN	4.66	0.21	0.9786	0.9	0.88074

Table 4.3: Mean exergy of solar photovoltaic energy technology across Southwest Nigeria

TIME	MEAN	C.F	PANEL OUTPUT	PF	OUTPUT ENERGY(Kwh/m2)
JAN	4.797	0.2	0.9594	0.9	0.86346
FEB	4.669	0.2	0.9338	0.9	0.84042
MAR	4.84	0.2	0.968	0.9	0.8712
APR	4.916	0.2	0.9832	0.9	0.88488
MAY	4.535	0.2	0.907	0.9	0.8163
JUN	3.583	0.2	0.7166	0.9	0.64494
JUL	3.584	0.2	0.7168	0.9	0.64512
AUG	4.144	0.2	0.8288	0.9	0.74592
SEP	4.09	0.2	0.818	0.9	0.7362
OCT	4.5455	0.2	0.9091	0.9	0.81819
NOV	5.085	0.2	1.017	0.9	0.9153
DEC	4.868	0.2	0.9736	0.9	0.87624
MEAN	4.471375	0.2	0.894275	0.9	0.804848

Table 4.4: Mean photovoltaic exergy on the Bight of Benin coast of Southwest, Nigeria

5.0. Discussion of Results

The solar energy technologies are the best mini – grid options with Techno – Economic Renewable Energy Viability Index (TEREVI) of 0.85 and 0.84 for photovoltaic technology and solar thermal power system respectively given high annual minimum all-sky insolation well above 4.0KWH/m^2/day for all locations and well suited for all forms of solar based electrical power generation and heating technologies such as Stirling engine, flat plate, parabolic plates, CSP and so on.

With an average irradiation of 4.66KWh/m^2/day for onshore and 4.55KWh/m^2/day for offshore in the Bight of Benin, consideration of a floating solar farm and island solar-wind farm hybrid energy system is strongly promising. The overall results of both onshore and offshore solar energy resource viability for commercial-scale solar PV power generation were excellent.

The result of tests by applying proven technical and economic feasibility tools such as TEREVI, Techno – Economic Levelized Cost of Electricity (TELCOE), Levelized Cost of Electricity (LCOE), and HOMER software simulated Cost of Energy (COE) yielded 850911132, 0.01886428, 0.019633, and 0.0133672 respectively based on a BESS – based 100KW model solar PV power plant which shows SPV – powered mini - grid is a very excellent commercially sustainable system. as can be seen in the All Sky insulations of table 5.1, October to May have the highest mean energies compared to the hearts of the rainy season lasting between June and September.

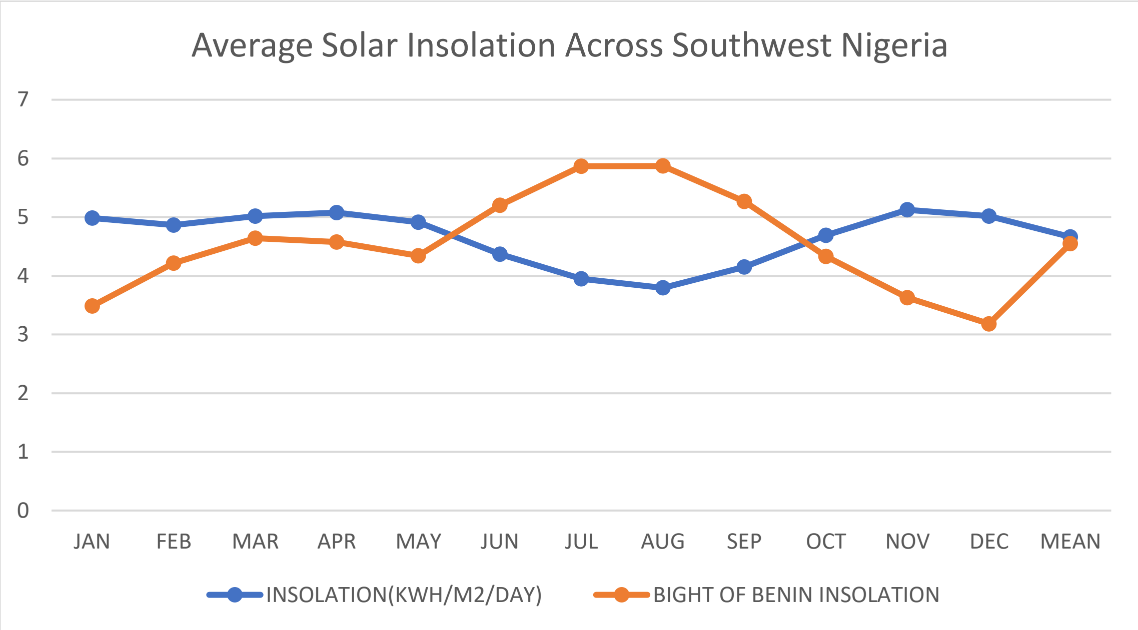

Figure 5.1

Being that floating solar power system is fast becoming a popular technology, Southwest Nigeria is blessed with high offshore solar insolation of about 4.9KWH/m^2/day as well as 32% of Nigeria's 853Km coastal line which makes it a good alternative energy system especially in locations with minimal environmental and social impact.

From the results of the energy models and simulations carried out, Solar PV system has the highest TEREVI value of 0.850911 while the feasibility barrier is 0.703, which is a pass mark abd makes it the all-round best renewable energy generating source and in corroboration has one of the smallest Cost of Energy values given \$0.0137782/kWh from Matlab Simulink, \$0.01886428/kWh for LCOE, \$0.01933/kWh for TELCOE, and \$0.016911/kWh from HOMER Optimization Software while the mean COE for all the sources is \$0.017296728kWh.

With an average potential of 135,502,198.50MWh, the mean GHI insolation in Southwest Nigeria is 4.66kWh/m^2/day and 4.87kWh/m^2/day at the mainland and Bight of Benin, respectively, which is much greater than the 1000kW/m^2/annum threshold required for commercial solar PV viability. This makes Solar PV a technoeconomically virile and attractive technology for mini-grid installation in addressing the electricity deficit in Southwest Nigeria, especially for households, rural communities, schools, health centres, and outdoor telecom infrastructures.

Being located in the tropical region, the variation of solar insolation and potentials across months, and designated stations, in Southwest Nigeria are as shown in Fig. .2, Fig. 4.3, and Fig. 4.4, respectively. The highest solar intensity occurs between October and March, with a mean monthly value of 108.436kWh/m^{2,} while June to September have the lowest insolation with a mean monthly value of 89.435kWh/m^2. This makes Southwest Nigeria year–round viable for solar PV electricity generation.

Though panel efficiency varies with technology, installation, tracking configuration, systems accessories, and brand, the average conversion factor of solar PV panels ranges from 0.18 to 0.24 which yields a mean of 0.21 used in the assessment of gathered data although there are now much more advanced panels of up to 45% or more with greater improvements likely in future. Coupled with the fact that Standard Test Conditions (STC) of most modules show optimal performance up to 32°C, Southwest Nigeria presents an excellent location for both residential and commercial scale solar PV electricity generation (Vourvoulias, 2025; Svarc, 2024).

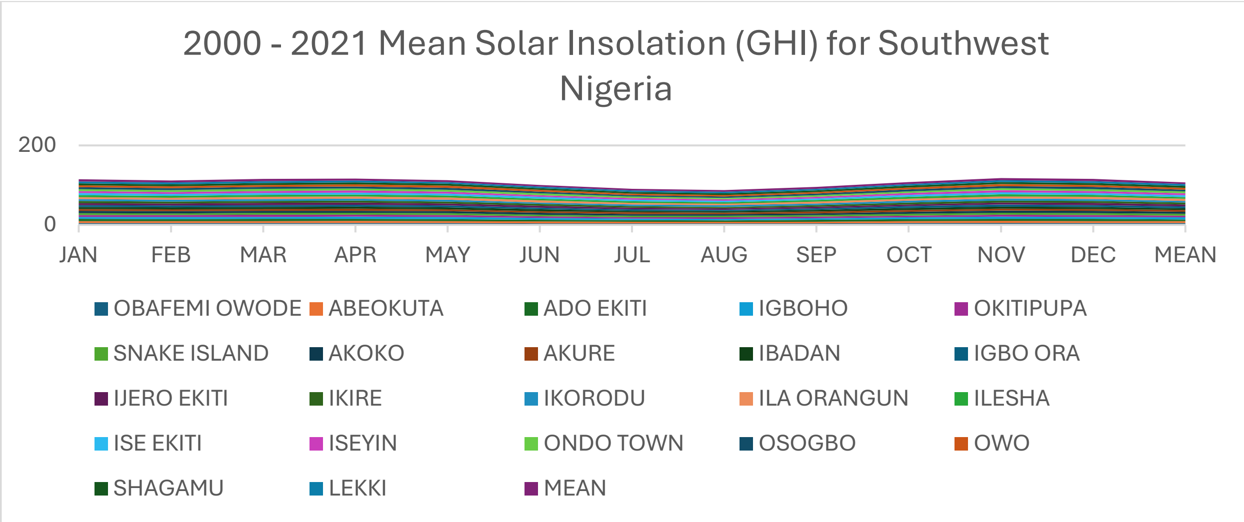

Figure 5.2: Mean Global Horizontal Irradiation across the mainland, Southwest, Nigeria

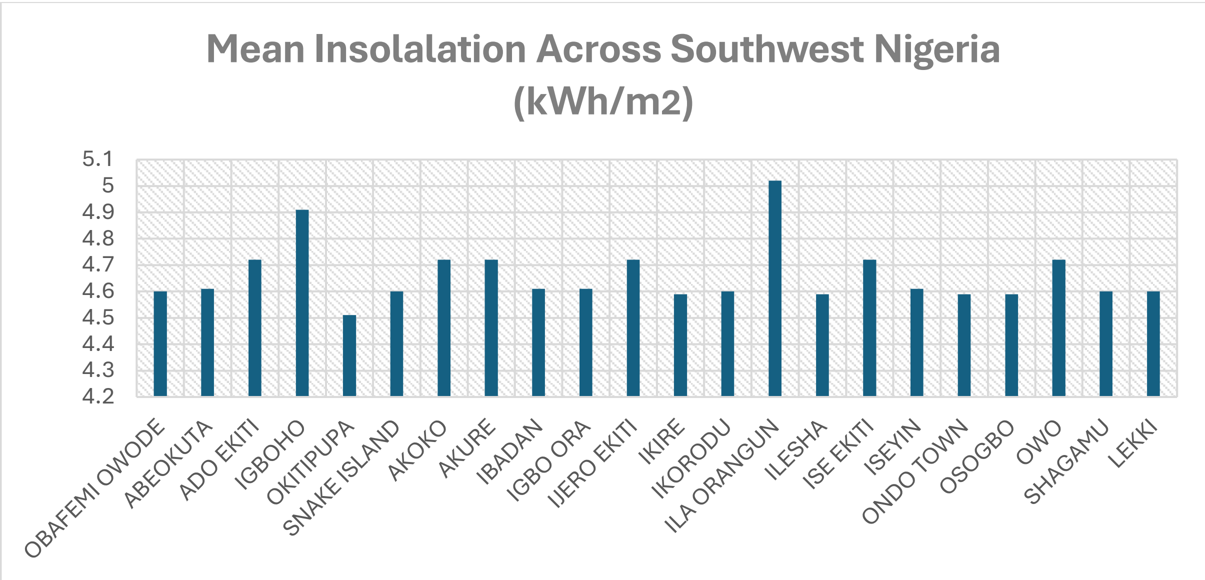

Fig. 5.3: Mean solar energy potentials across Southwest, Nigeria

6.0. Conclusion and Recommendation

Solar PV is a veritable means of sustainable commercial-scale electric power generation in all areas of Southwest Nigeria, especially via networks of mini–grid in BESS-based configuration, given the very high solar insolation rating of the region, being greater than the 4.0 kWh/m^2/day threshold. The TEREVI is a very powerful and conclusive model for deciding the viability of solar photovoltaic mini-grid being as all constraints and local peculiarities are addressed compared to existing tools that have not practically addressed hidden pitfalls that made over 97% of commercial solar projects to fail in Sub-Saharan Africa.

Given the simplicity of SPV as well as its near zero emission and safety, it is best to focus installation with unserved, unconnected, rural, remote, stranded, and exclusive communities as priorities to ensure energy efficiency and build the power plants in modules of say not more than 10MW - 100MW clusters in interoperable catenations of ≤100kW mini-grid units. These 100kW mini-grid units will serve as autonomous community energy systems. The ‘village-by-village’ like ≤100kW mini-grid units’ photovoltaic systems may be standalone or interconnectable in catenation with those of neighbouring communities as well as interoperable with the national grid for the sales of excess power generated. This

It is urgently imperative for governments at all tiers to prioritize the acquisition of renewable based meteorological data with as many local stations as possible with at least 5 evenly placed across each state of the federation less than 10,000Km^2 or 10 in states above 10,000Km^2 area and proper renewable energy mapping made to guide urban and regional planning to enable and enhance the exploitation of local renewable energy resource in high – potential areas in the short, medium, and long term.

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