Design and Simulation of a Solar Photovoltaic Mini-Grid along with Estimation of Carbon Emission Mitigation Using Retscreen Tool

[*1,4]Joy Eneh, [1]Nanev Aondofa, [1,2,3]Izuchukwu Okafor

[1]Africa Centre of Excellence for Sustainable Power and Energy Development, University of Nigeria, Nsukka

[2]National Centre for Energy Research and Development, University of Nigeria, Nsukka

[3]Department of Mechanical Engineering, University of Nigeria, Nsukka

[4]Department of Electronic and Computer Engineering, University of Nigeria, Nsukka

[*]Corresponding Author

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ABSTRACT

Solar photovoltaic, being one of the cleanest forms of renewable and sustainable energy, has been very instrumental in every nation's Energy Transition Plan (ETP). This study is aimed at a pragmatic demonstration of energy transition, utilizing solar photovoltaic system that could curtail reliance on fossil-based power generation and hence, estimating the measure of carbon emission mitigated by this renewable energy project. This study illustrates a conceptual design of a solar photovoltaic mini-grid with detailed step-by-step analysis and visualization of the entire circuit structure of the solar photovoltaic mini-grid. The mini-grid captures a capacity of 159kWp PV array and 600kWh of energy storage, which would cost USD306,090.56, with a potential of mitigating 255 tons of GHG emission yearly. The methodology used in the implementation of this study includes data collection from the proposed facility to be powered by the mini-grid, data analysis for sizing and selection of the grid components, grid system representation and visualization by means of a Single Line Diagram (SLD), detailing all circuit components with connections and configurations. The results presented include the estimated carbon emission that would be mitigated by the physical implementation of the designed mini-grid, hence reflecting the whole essence of energy transition.

Key words: solar photovoltaic mini-grid, energy transition, carbon emission, energy storage

INTRODUCTION

The global concern for climate sustainability is growing in terms of awareness, attention and alarm with each passing time. The world has come to a sober realization that human and industrial activities implemented to meet energy demand on earth have posed traits to the well-being and sustainability of our climate. This situation, if unattended, will inhibit the availability of a conducive environment now and for generations to come. Before the natural climatic state of the planet earth was altered, solar radiation would travel from the sun to the earth in short wave lengths. A proportion of this radiation would be absorbed by the earth in form of light energy while the other would be reflected backinto the atmosphere in longer wave lengths, where they would escape back into space unimpeded. This natural cycle kept the earth's atmosphere at a balance, not exceeding safe temperature range and neither falling below it, then came the burning of fossil fuels and industrial revolution which brought about an alteration in the natural cycle and balance of our climate.

The yearning need for generation of energy, which is the driving force of every economy all over the world, has led to human activities ranging from local and direct combustion of bio materials to industrial combustion of fossil fuels like coal, oil and gas to generate energy, be it electrical, mechanical, thermal etc. These energy generation processes facilitate consistent emission of Green House Gasses into the earth's atmosphere. These greenhouse gas emissions are constituted by gases such as Carbon dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O), Sulphur hexafluoride (SF_6), Hydrofluorocarbon (HFC) and Perfluorocarbon (PFC)[1].These gases, broadly referred to as carbon emissions, have formed a layer over the atmosphere that impedes the escape of reflected solar radiation from the earth into space, hence an alarming proportion of reflected solar radiation remains trapped within the earth's atmosphere, resulting to global warming.Scientific records have it that greenhouse gases have caused a global increase in surface temperature reaching an average of 0.11^0 Fahrenheit (0.06^0 Celsius) per decade since 1850 or about 2^0 F in total [2].

The international community, in response to these traits posed by climatic change, came together in a historic coalition known as the Paris Agreement[3]. This was a round-table consensus held in 2015, where nations around the world agreed to take responsibility of averting the experienced climate change by means of carbon mitigation and carbon absorption in the earth's atmosphere. It was clear that the only way to achieve this daring feat and restore our climate to its natural climatic condition is for every nation to implement energy transition plans (ETP) targeted at reaching a NetZero carbon emission by 2060. The Paris Agreement catalyzed the necessity and development of renewable energy systems for climate sustainability. Every nation that is part of the Paris Agreement has renewable and sustainable energy as its cardinal tool for energy transition. Hence, all over the globe, renewable energy systems are being deployed to replace the existing harmful sources of energy, thereby producing clean energy also known as green energy with zero carbon emission into the atmosphere.

Since the birth of the first photovoltaic cell 1954[4], Solar Photovoltaic technology has undergone a tremendous feat of development from micro units of solar photovoltaic systems to the present-day record peak capacity of 2.8GW Golmud solar energy plant in China. Solar photovoltaics have been one of the most instrumental forms of renewable energy generation which fosters the mitigation of carbon emissions into the atmosphere. It generates clean energy with zero carbon emissions and it utilizes solar radiation from the sun, rendering it a renewable, reliable and sustainable form of energy generation.

Nigeria, like most developing countries, has faced the challenge ofinsufficient power generation and transmission from time immemorial. Owing to the epileptic state of power availability in the country, the use of diesel generators in this part of the world has been remarkably prominent. The country's main source of power generation has been hydropower plants and thermal power plants. However, a great percentage of the country's populace has no access to electricity, hence yielding to off-grid individual power generation by the deployment of diesel generator plants.

This study aims at a replacement of off-grid fossil fuel power generation with solar photovoltaic mini-grids, estimating the measure of carbon emission mitigation in the proposed environment.

Theoretical Concept

A solar photovoltaic mini-grid is a photovoltaic plant with a localized distribution network to a unit, village or cluster of villages, Providing renewable energy, independent of the national grid[5].Solar photovoltaic technology deals with direct conversion of sun light to electrical power through a phenomenon known as photoelectric effect or photovoltaic effect.[6][7] Photoelectric effect, as applicable to solar photovoltaics, takes place on solar cells. Multiple solar cells, connected together, form a solar photovoltaic panel. Direct current is produced when sun light is incident on a PV array. The load powered by a mini-grid comprises of various stratifications and capacities with all categories of electrical load being either direct current load (DC) or Alternating Current Load (AC), however a mini-grid is structured to supply alternating current power and also store energy which utilizes direct current, hence resulting to circuit structure consisting of photovoltaic array (PV array), Solar charge controllers, inverters and a battery bank for energy storage.

PV array

The building block of a Mini-grid's photovoltaic array begins with a solar cell. A connection of multiple solar cells constitutes a PV module or solar panel. A series connection of multiple P V modules constitutes a PV

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string, while multiple PV strings, connected together, constitutes a PV array. The flow diagram for the structure of a PV array is illustrated in Fig 1. The PV array, in solar photovoltaic mini-grid, serves as an interface where solar radiation is harnessed and converted into direct current electricity. The size and capacity of a PV array, which is estimated in kilowatt peak (KWp), varies from one mini-grid to another, depending on the capacity of the mini-grid.

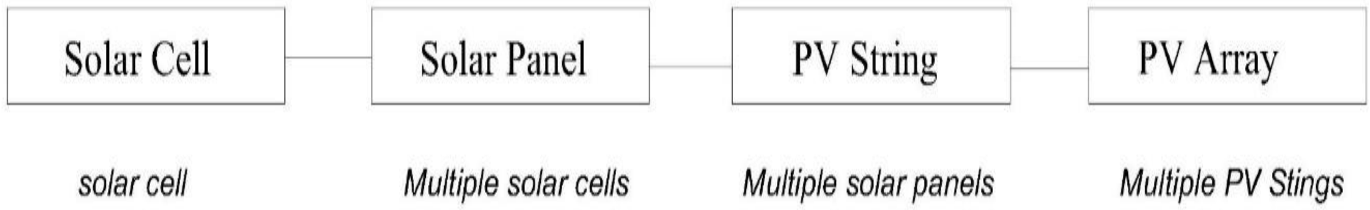

Fig.2.1 structure of a PV array

Inverter

Most especially in mini-grids, direct usage of DC power generated from a PV array is not obtainable in practice. In all cases, the intended load profile to be powered by a mini-grid comprises various appliances which require alternating current inputs. Hence, the need to convert the generated DC power from a PV array to alternating current power gives birth to the application of inverters in solar photovoltaic mini-grids. By method of inversion, the DC power from a PV array is inverted to AC power utilizing a set of solid-state switches-MOSFETS or IGBTs-that essentially flips the DC power back and forth, creating AC power[7]. Design and implementation of solar photovoltaic mini-grids essentially deploys utilization of inverters for both off-grid and grid-tied applications. In practice, inverters are grouped into hybrid and non-hybrid inverters, where the former comes with an inbuilt MPPT solar charge controller while the latter has to be applied in a system that would utilize a separate and independent charge controller [8].

Maximum Power Point Tracker (MPPT) Charge Controller

The set up of a solar photovoltaic system, in general, utilizes PWM and MPPT solar charge controllers. PWM, which are the traditional charge controllers, have limitations which inhibits flexibility, stability and reliability when it comes to large scale applications such as mini-grids. The operation of PWM charge controller is more like that of a relay switch, allowing charge current into the battery bank only when the PV array voltage matches the voltage of the battery bank [9]. Considering that the intensity of solar radiation incident on a PV array varies through the day, the maximum power of the PV array correspondingly varies as well, hence continuous and effective charging cannot be achieved with PMW charge controllers for large storage applications like mini-grids. MPPT solar charge controllers, which are enhanced state-of-the-art charge controllers, executes the task of charge controlling at remarkable level of flexibility and reliability. They have the advantage of accommodating higher PV array capacities, thus they track the maximum power point at every given time during the day and vary the current with the voltage to deliver the needed current into the battery bank. They are, in their own rights, some sort of DC transformers, converting excess PV array volage to deliver adequate charge current.

Battery Bank (Storage)

The relevance of lithium battery technology for storage applications in solar photovoltaic mini-grids cannot be overemphasized. Considering their exceptionally superior performance characteristics and conformity with the demands of trending renewable energy systems, lithium-ion batteries are indispensable for the efficiency of PV Mini-grids [10]. Unlike the traditional lead-acid batteries, lithium-ion batteries offer high energy density, comparatively storing more energy per unit weight and volume. This attribute brings about flexibility in the design and implementation of PV mini-grids, where space and weight can be limiting factors. In addition to their longevity, they can safely accommodate a deeper Dept of Discharge (D.O.D) without the risk of

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shortening their life span. Lithium-ion batteries have a high rate of charge (R.O.C) which facilitates adequate energy storage during peak-sun hours. To cap it all, lithium-ion batteries are more inclined towards climate sustainability in terms of energy efficiency and reduction of lead exposure which is a harmful substance.

Design Analysis

This work, aimed at a pragmatic demonstration of solar PV utilization for energy transition, has its case study at the hospital facility in Zurmi local government area of Zamfara State. The facility is totally off grid and it uses a 65KVA diesel generator plant. The methodology begins with load profile analysis with information as obtained via the data logger at the facility.

Table 2.1 load profile from data logger

Hour	1	2	3	4	5	6	7	8	9	10	11	12
Power (W)	35.340	31.780	31.200	30.750	30.930	29.460	28.490	29.380	34.750	35.310	36.080	36.320

Hour	13	14	15	16	17	18	19	20	21	22	23	24
Power (W)	36.600	37.200	36.770	37.980	35.550	38.840	35.590	34.180	33.660	34.460	35.860	33.820

The daily average power consumption of the facility is 38.84Kwp. For possibilities of unforeseen load increment, the daily peak power consumption would be estimated with a 25% tolerance, which is 48.54Kwp. hence the design would be such that the daily power consumption does not exceed 60% of the mini-grid's capacity. The battery bank would have up to 15 hours autonomy.

The PV system has been structured into to two subsections to enhance reliability and stability. The first section has a PV array of12 strings with each having a series connection of 15 Nos. of JAM72S30-545MR Module, hence constituting a PV array of 98.1KWp. A typical JAM72S30-545MR Module has the following specifications at STC: Pmax = 545W, Voc = 49.75V, Vmp = 41.80V, Isc = 13.93A, Imp = 13.04A. Therefore, the operating string current of the array is 13.04A while the array's total operating current and operating voltage will be obtained as:

Imp (Array) = Imp (Module) × Number of Strings = 13.04 × 12 = 156.48A

Vmp (Array) = Vmp (Module) × Number of modules per string = 41.80 × 15 = 627V

Output from the PV array is fed into 3 sets of 27kw Hybrid inverter (Fronius Eco) via a 6-way DC combiner box. (i.e. A string-combiner-inverter ratio of 4:1:1).The Fronius Eco supports a maximum PV generator power of 37.8KWp, a direct current input of 47.7A and DC input voltage range of 580-1000V. The three inverters, in a parallel combination, will give out an AC output in common phase.

The second section of the PV systemhas an array of 16 strings. Each string has 7 modules of JAM72S30-545MR connected in series. Output from the PV array is fed into 6 sets of 10KVA/48V Victron inverters via 5 sets of Victron MPPT RS450/200 solar charge controllers.

The charge controllers regulate the charge current into a 600KWh battery storage. The battery bank has 128 cabinets of 4.8Kw, 48V UP500 Pylontech Lithium-ion batteries connected in a single stringto yield 600KWh. Alternating current output from both sections are fed into a synchronization panel which will regulate the outputs from both supplies to give out a single output.

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Single Line Diagram

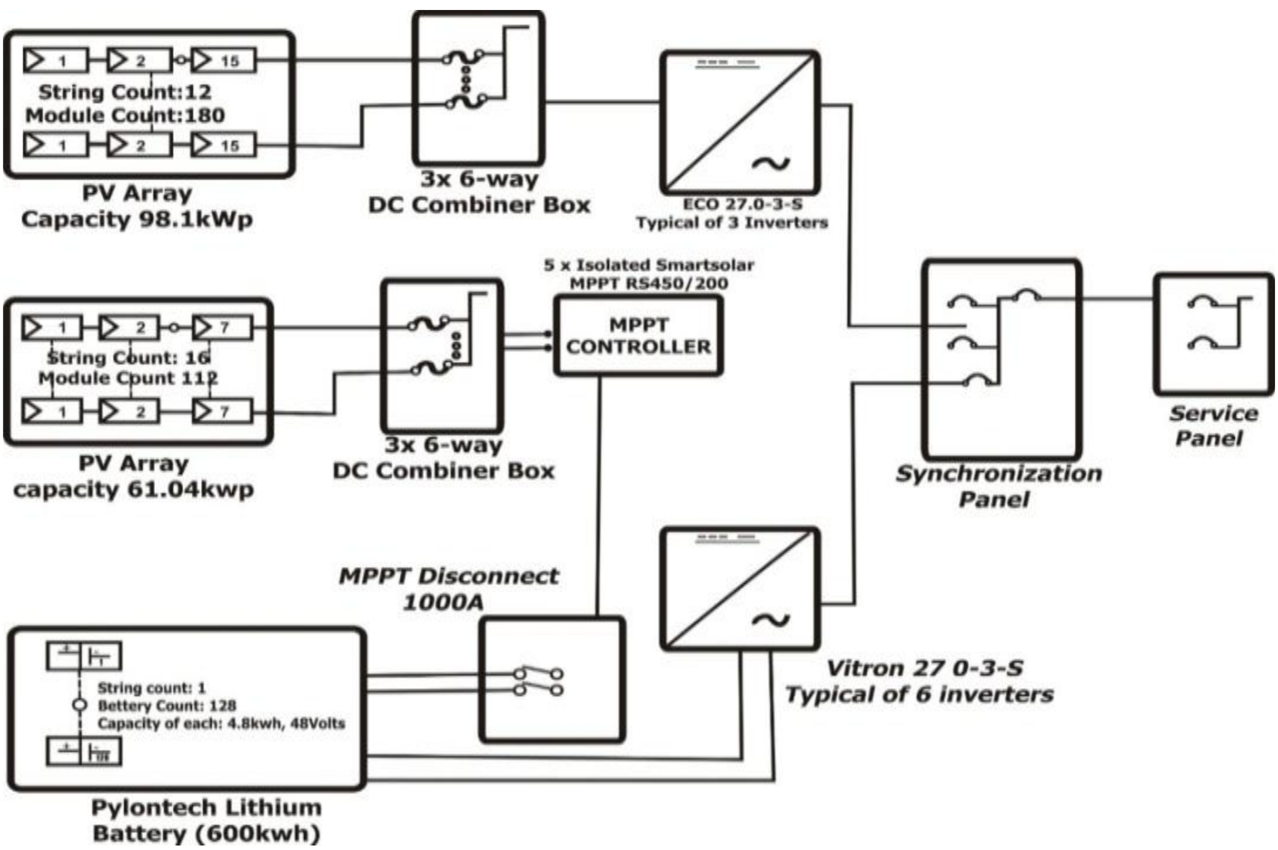

Fig. 3.1 Single line diagram of mini-grid structure

Simulation Results

The 98.1KWp and 61.04KWp sections of the photovoltaic system were simulated independently using PVsyst Photovoltaic Simulation Software. Both sections generate power independently of each other, combining their output at the synchronization panel to act as a single system.

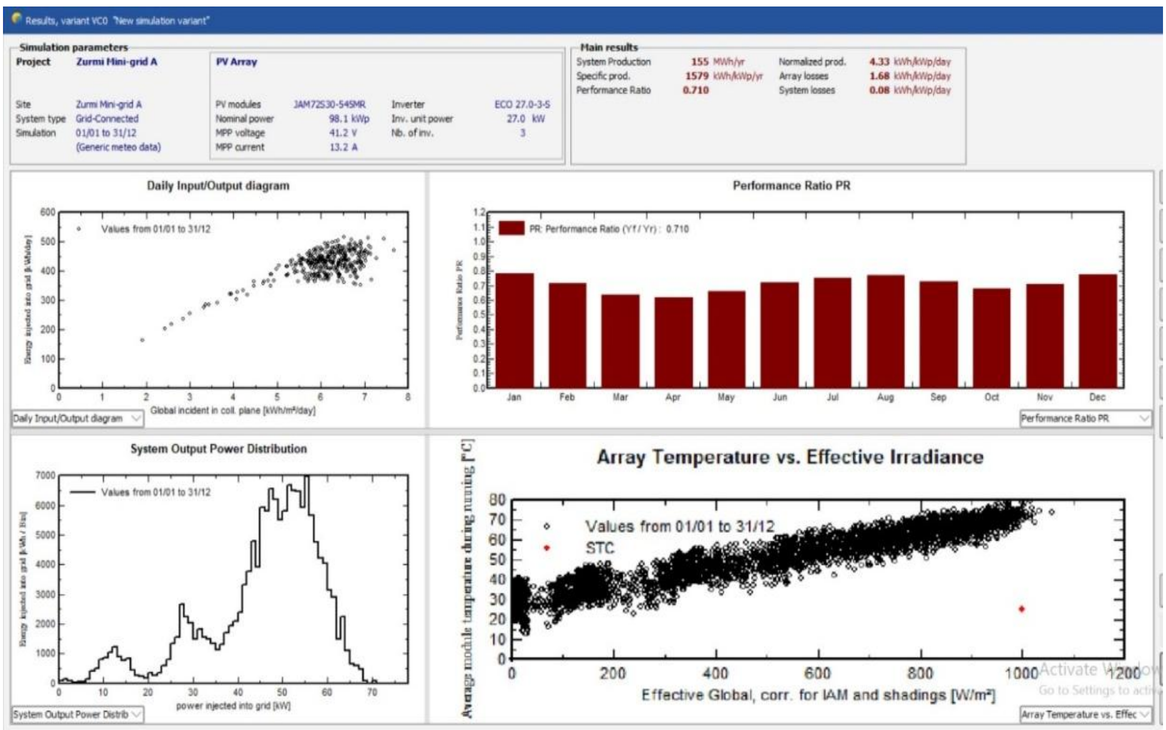

Fig 4. Simulation variant for 96.1Kwp section

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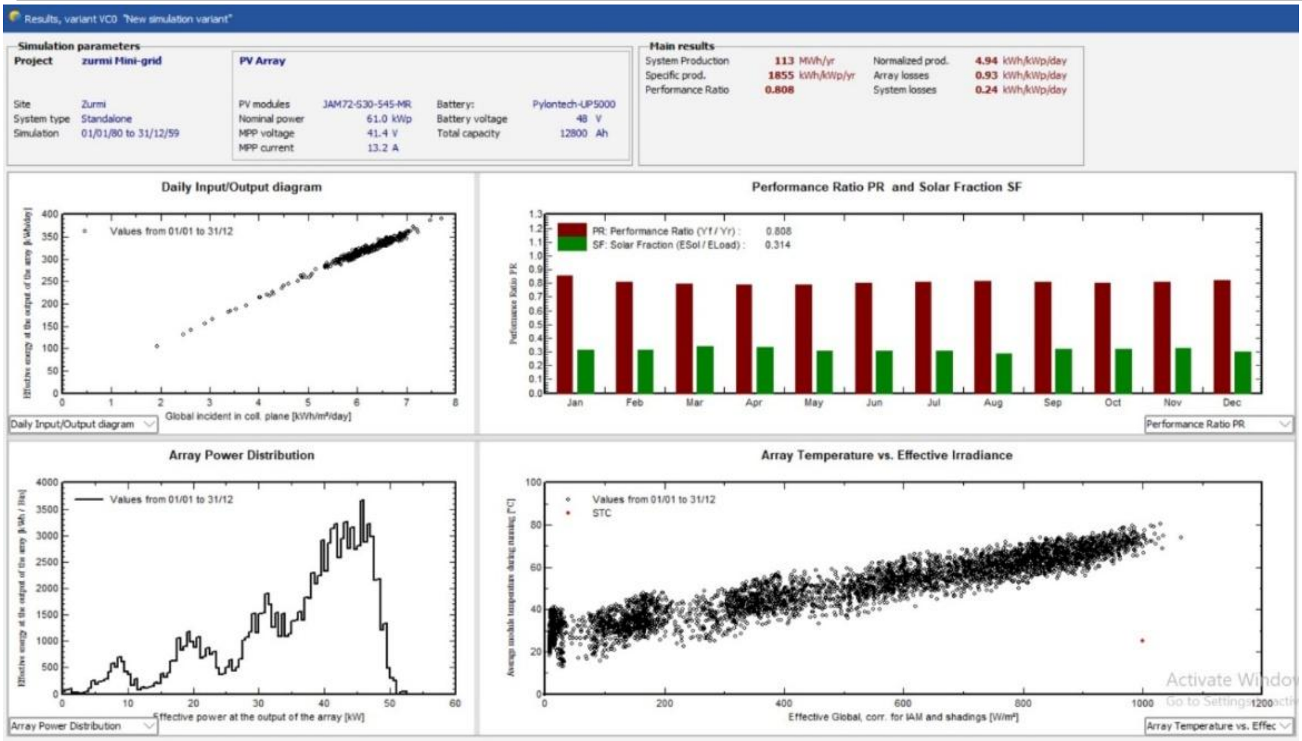

Fig.5 Simulation variant for 61.04 KWp Section

The Simulation results as presented validates the system design, performance and functionality.

Estimation of Carbon Emission Mitigation

RETScreen Expert net zero planning software was used to simulate the 159KWp solar photovoltaic design. RETScreen Expert models the energy designs, presenting feasibility analysis ranging from location, facility, energy, cost, emission, finance, and risk. The cope of this project, in relation to energy feasibility, is specific on carbon emission.

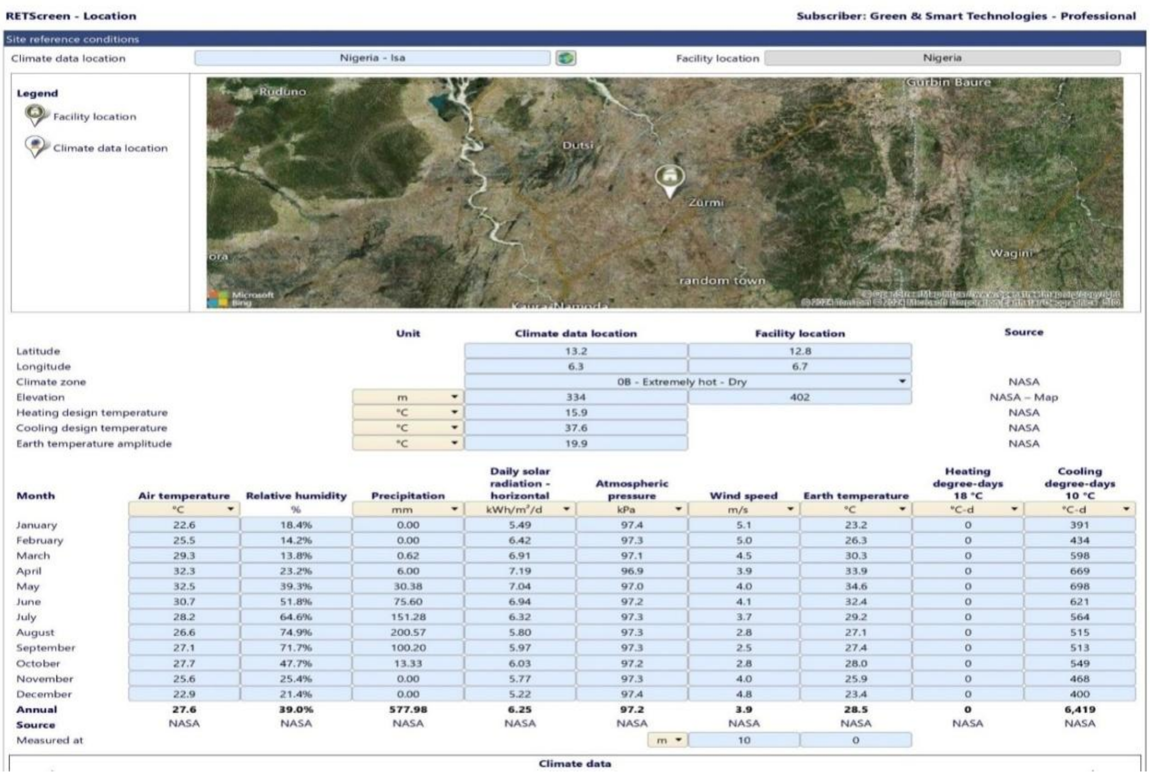

Fig. 5 RETScreen location and climate data results

RETScreen establishes a baseline scenario which represents the energy consumption and associated emissions before implementing the energy project. The software considers the types of fuels or energy sources used in the baseline scenario, such as electricity from the grid, natural gas, oil, coal, etc. like IPCC (Intergovernmental Panel on Climate Change) or national agencies. RETScreen analysis of the designed mini-grid would mitigate 255 tons of GHG emissions yearly which is equivalent to 549 barrels of crude oil in with reference to the base case. The emission analysis for this design is presented in fig.6

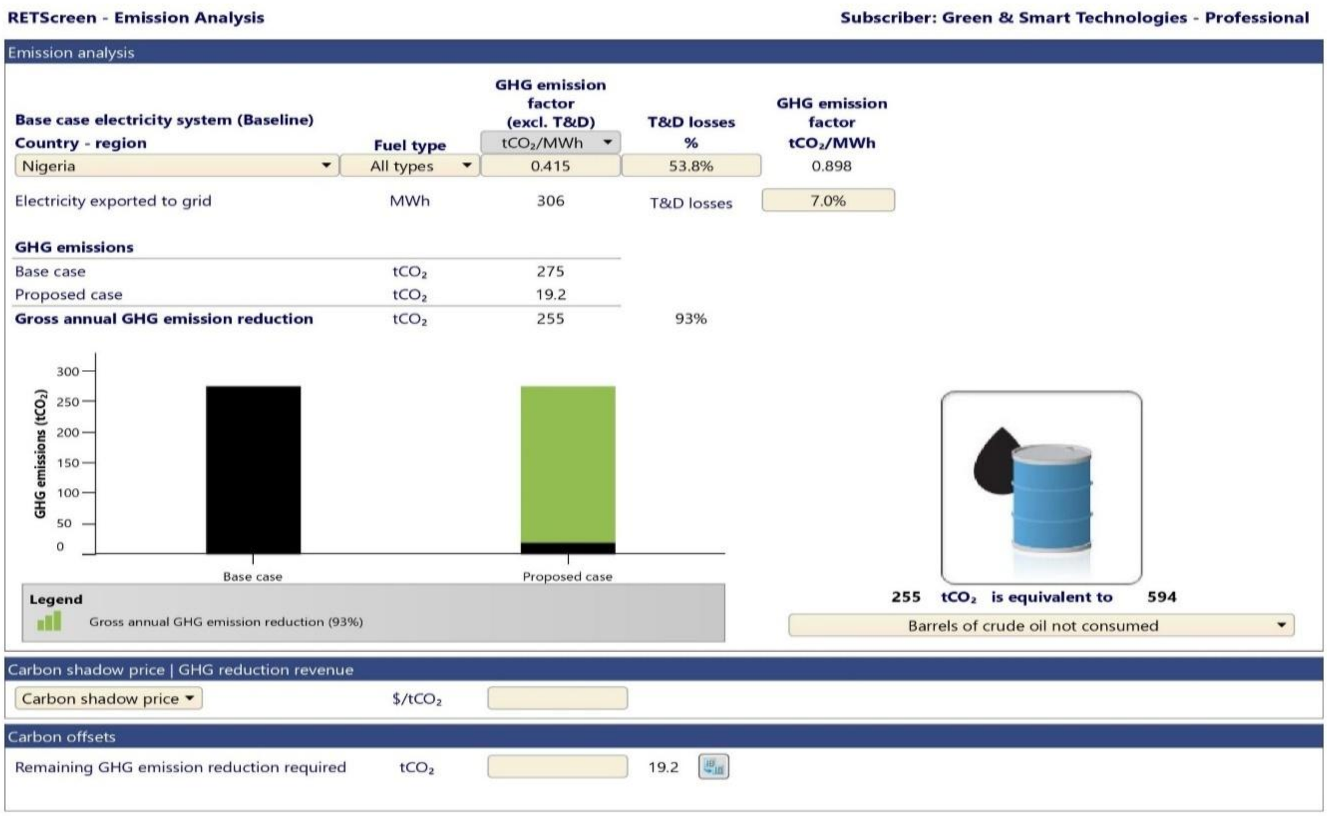

Fig. 6: Emission Analysis result

Implementation Road Map

Medecins Sans Fontieres (MSF) plays a critical role in Nigerian hospital by providing medical assistance and support mostly in underserved areas and during emergencies. Zurmi hospital, being an area of insurgence, is one of the Nigerian hospitals supported by MSF. The implementation road map for physical implementation of this project is based solely on approaching MSF for funding. MSF is fully aware of the energy challenge that Zurmi hospital facility is faced with, being off the national grid of electricity supply. We are confident on drawing their attention to the glaring need of such a project.

Cost of Implementation

Table 3.2 Cost of Solar PV mini-grid Implementation

Item	Description	Total cost	Currency
A	Equipment and Installation Supply	218,977.67	USD
B	Installation and Commissioning	24,889.40	USD
C	Civil works	68.220.00	USD
D	Documentation and User + O&M Manuals/Training	9,333.52	USD

E	Two-year Maintenance Service	52,889.97	USD
	TOTAL PROJECT COST	**306,090.56**	**USD**

All aspects involved in implementation of the designed mini-grid are as summarized in table 3.2. The total cost of implementation amounts to USD306,090.56

CONCLUSION

The deployment of solar photovoltaic technology in mini-grid applications is very essential for meeting energy needs and energy transition goals in Nigeria. This research work has demonstrated a conceptual design of solar photovoltaic mini-grid in the case study of Zurmi hospital facility. The 159KWp capacity mini-grid, its design functionality verified by successful simulation and results, can affect a carbon reduction of 225 tons annually as obtained from RETScreen emission analysis. This quantity of carbon emission that would be mitigated by implementation of this design is equivalent to 549 barrels of crude oil in comparison. This has a significant positive effect on the gross dependence of Nigeria as a nation on power generation from fossil fuels.

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