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ELECTRIC POWER GENERATION DESIGN AND ESTIMATION USING PHOTOVOLTAIC TECHNOLOGY

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Abstract- Electric power is an essential commodity required for the socio-economic transformation of developing countries like Nigeria. As of 2019, the world bank report puts access to electric power in Nigeria at 55.4%. Having abundant renewable energy resources and being a major exporter of crude oil, these statistics show the lack of investments and policy direction in the electric power sector of Nigeria. This research proposes two electric power generating systems based on photovoltaic technology. The two systems are to generate electric power for residential and commercial grid-connected applications. The grid-tied system generates 6 MW of electricity while the residential system generates electric power based on the power needs assessment. Both systems are sited in Doko in the Niger state of Nigeria. The viability of the proposed system is determined by two highly rated, industry and academia accepted PV software known as PVsyst and HelioScope. Both software uses real-time site location to determine the expected daily, monthly and yearly electric energy of the proposed PV systems. With yearly global horizontal radiation of 1931.3 kWh/m^2, the grid-connected system generated 9.77 GWh of energy yearly, with an average performance ratio of 84% using PVsyst. HelioScope produced 7.244 GWh of energy with a performance ratio of 76.17% annually.

Keywords: Grid-Connected, HelioScope, Photovoltaic System, Stand-Alone, PVsyst, PV Power-Plant.

1. INTRODUCTION

Nigeria is located in the Sub-Saharan region of West Africa, along the coast of Gulf of Guinea. Unlike other African countries, Nigeria is a federal republic with 36 (thirty-six) states. The current population of Nigeria is about 215 million [1] with annual average growth of 2%. Nigerian economy is highly dependent on crude oil exports which grows annually at a rate of 6%. Nigeria is blessed with multiple resources for electric power generation and other mineral resources that its' yet to fully harness for economic development. Electric power generation and penetration in Nigeria is the not best for a country with the biggest economy in West Africa.

From thermal resources such as gas and oil, to renewable resources such as wind, hydro and solar; these combined sources can generate close to 12.522 GW of electric power if properly planned. Lack of investment and poor maintenance are hugely responsible for stunted growth of the electric power sector in Nigeria. 4000 MW of electric power is the biggest magnitude of power dispatched on most days. Households, commercial and industrial firms auto-generate 40% of the 13 GW of standby diesel generator based electric power [2-3]. Figure 1 shows the electric power generation mix in Nigeria as at the end of 2021.

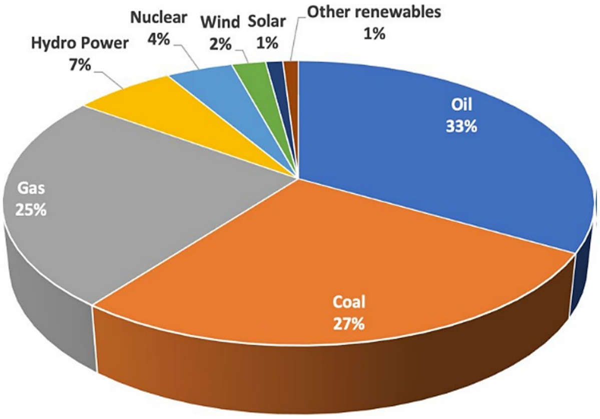


Figure 1. Generation mixes in Nigeria [1]

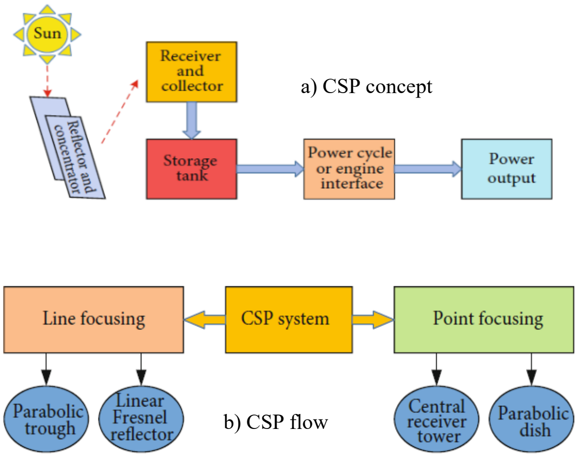
Even though Nigeria has abundant reserves of crude oil, price fluctuations in world crude prices poses adverse effects on the pricing of electric power generated from crude oil, also negative effects of fossil fuels on the environment has brought forth the urgent need for integration of renewable energy sources for electric power generation. Hydro, wind and solar resources are the major renewable energy resources heavily available in Nigeria. Hydro and wind require huge monetary investment and are mostly suitable for largescale electric power generation. Other forms of solar energy such as CSP (concentrated solar power) also requires huge monetary investment and are also suitable for largescale power generation.

Photovoltaic systems on the other hand require relatively small monetary investment for small or individual systems and small to medium monetary investment for large scale electric power generation. Comparing PV systems to hydro and wind, PV installations do not require specialized land conditions for installation, PVs can be installed on roof tops or on the ground and they will adequately produce rated power provided they are not affected by shading. Hydropower installation requires special land features which can support the building of the dam to retain water all year round and also provide the needed kinetic motion required for rotor blade rotation. Hydro dams cannot be sited close to consumers unless the water resource is close to the consumer hence huge financial investments are required for transmission lines. Long transmission lines produce power losses [3-5].

The electric power sector in Nigeria is divided into three categories i.e. generation, transmission and distribution sectors. The generation sector is composed of 23 public and private generation companies. These generation companies are made up of hydroelectric and thermal power plants. The generation companies have the potential to produce 12,522 MW of electric power, however, the average production is 4,000 MW. The transmission lines cover a distance of 20,000 km with a wheeling transmission capacity of 8,100 MW. At the distribution end, only 25% of installed capacity is supplied to the consumer [6].

2. SOLAR ENERGY

Energy from the sun known as solar energy which is composed of heat and radiant light has been used by humans since the inception of time. It has provided energy for plant growth, light for illumination, drying, processing and preservation of food etc. Solar energy has been found to be a clean, naturally reoccurring source of generating electricity hence classified as a renewable energy. Solar energy as it knows today is used in generating electric power, used in solar architecture and thermal energy applications. 885 million TWh of solar energy is received on the earth surface yearly.



a) CSP concept

b) CSP flow

Figure 2. Concentrated solar power [6]

With respect to electric power generation, several techniques such as concentrated solar power (SCP) and PV systems are used. Figure 2a shows the concept of solar concentrated power while Figure 2b shows CSP flow diagram [6-8].

2.1. Photovoltaic Systems

Photovoltaic systems are also known as PV system or solar array, photovoltaic power systems or solar PV systems. Photovoltaic system is a technology which directly converts solar energy into electric power by the use of solar panels or modules. "Photovoltaic" is a combination of two words i.e. photo and voltaic which means light and voltage accordingly. The primary component of photovoltaic systems is the photovoltaic cell. Basically, solar cells (photovoltaic cell) use photoelectric characteristics (also known as photovoltaic effect) to generate or convert solar energy into electric power without applying any type of generator or engine. When solar energy (irradiance) falls on the surface of solar cells, separation of negative and positive charge carriers occurs due to electric field produced in the cell. Photons cause the breakaway of electrons thus cause electron flow which is known as electric current. Figure 3 shows electric current generation from a solar cell. Higher number of photons causes the current flow to be huge and therefore higher magnitude of electric current is generated [9-11].

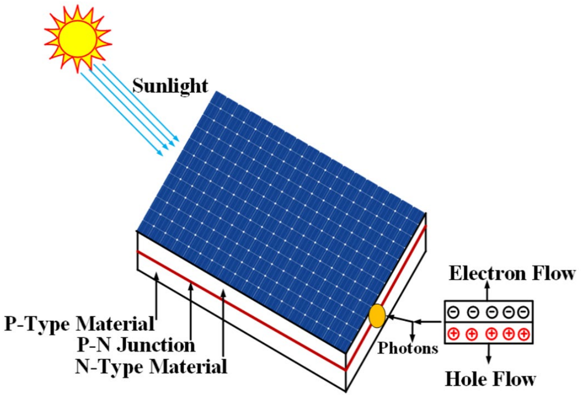


Figure 3. Photovoltaic cell

2.2. Photovoltaic Cell

Photovoltaic cells also known as solar cells are mostly designed from semiconductor materials such as silicon (Si). Various technologies have given rise to different types of solar cells. Below are some of the commonly used silicon based solar cells [12]:

- Bar-crystalline silicon
- Thin-film technology
- Copper indium diselenide
- Monocrystalline
- Cadmium telluride
- Polycrystalline
- Laser grooved buried
- Triple-junction amorphous

Figure 4 shows equivalent circuit or model of a solar cell. The circuit arrangement is made of parallel connected ideal current source and real diode at the input section.

The current source produces current directly proportional to the magnitude of irradiance received. The parallel current source-diode network is connected in series to a series resistance. From Figure 4, I_{ph}, I_d and I represent the cell, diode and output currents accordingly, the output voltage is given by V, R_s and R_p represent series and parallel resistance, the cell temperature and irradiance are expressed by T and G_a accordingly. Equations (1) and (2) show the current and voltage relationship of Figure 4.

$$I_{ph} = I_D + I \tag{1}$$

$$V_D = V_s + V \tag{2}$$

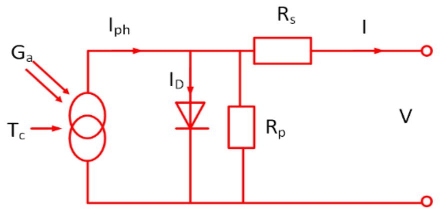


Figure 4. Solar cell equivalent circuit

Solar cells constitute the building block of photovoltaic systems. The size of solar cells has been increasing since the year 2012 where the average size of a cell was 156×156 mm. New solar cells introduced in the year 2020 have 210×210 mm dimension. A number of cells are connected in series/parallel arrangement to produce solar modules. Again, parallel/series connection of modules produce solar panels. An array of photovoltaic system is composed of solar panels connected in series or parallel or both to derive specific voltage-current magnitude. These arrangements are illustrated by Figure 5.

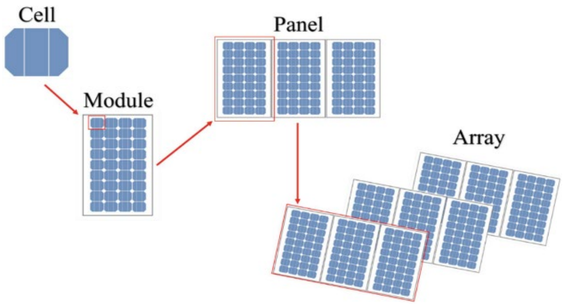


Figure 5. Solar cell/module arrangement

2.3. Types of Photovoltaic System

With respect to grid connections, photovoltaic systems are classified as standalone or grid-tied PV systems. There's the third type which is a hybrid system where other forms of energy generating sources such as diesel or wind power are used to augment the required power. However, current advances in battery technology provides better prospects in utilizing PV systems alone. Large units of battery systems can provide solar power during periods of redundancy of solar panels i.e. during the night, cloudy and rainy days. Standalone systems are mostly designed for residential, off-grid and small business establishments. The power produced in standalone systems are either immediately used or stored in energy saving systems such as batteries. Grid-tied or connected PV systems are usually of commercial size and generates high voltages for three-phase distribution or transmission lines. With appropriate safety devices and metering systems, excess power from standalone systems is connected to the grid in some advanced countries.

3. SOLAR PV PROSPECTS IN NIGERIA

Weather conditions in Nigeria perfectly supports PV applications all year round. The northern part of Nigeria provides the best location with respect to weather conditions for photovoltaic applications. According to the global horizontal irradiation map of Nigeria, the daily and yearly irradiation ranges between 4.2-6.2 kWh/m^2 and 1534-2264 kWh/m^2 accordingly. The average monthly values are expressed in Table 1. Several publications have been made to show the potential of PV applications by investigating existing PV installations and providing projections for future installations. Currently, the largest PV installation is a 10 MW power plant located in Kumbotso, others are 3.5 MW plants located in Makurdi and Kano accordingly, 2.35 MW and 2MW plants located in Ijebu Mushin and Awka respectively. Several rooftop PV installations are scared across the country.

Table 1. Average monthly global horizontal irradiation

Month	Jan.	Feb.	Mar.	April	May	June
GlobHor (kWh/m^2)	177.9	165.5	186.3	173.4	168.3	147.6
Month	July	Aug	Sept	Oct	Nov	Dec
GlobHor (kWh/m^2)	137.6	132.1	136.5	158.7	171.6	175.8

Authors in [13] investigated residential photovoltaic systems in Lagos city in Nigeria. They established that PV systems are location specific and therefore are affected by factors such as localized system cost, solar radiation and energy requirement. The results of the research showed that residential PV systems provide the best cost benefit investment when compared to other sources of electric power generation such as generator sets. In [14], the authors evaluated 148.5 kWp grid connected PV systems for use by the Local government of Nigeria. The grid connected system has energy saving components. To analyze the system performance, PV*SOL software was used. The result of the evaluation shows that the output energy of the system matches the output energy of the software. 70% of the generated power is exported or sold to the national grid since the secretariat requires only 30% of the produced power. Off grid comparative analysis and feasibility studies for rural electrification is presented by [15]. This paper establishes that decentralized electric power generation for rural application can improve the quality of life substantially at a reduced cost and environmentally friendly manner. Renewable energy sources such as wind, hydro and PV systems and diesel generators as standby systems provide means of electric power generation for rural off-grid applications. The months of March and May yielded the highest magnitude of voltage exported to the grid for a proposed 75 MW photovoltaic power system in Nigeria [16].

The proposed PV system is investigated by the authors to establish its suitable for the proposed location of Kankia which is located in the Nigerian state of Katsina. Using NASA based meteorological data, the proposed PV systems delivers electric power of about 8374.4 to 11336 MWh yearly with yearly average efficiency of 74.5%. Other PV related research in Nigeria can be found in [17-22].

4. SYSTEM DESIGN AND SIMULATION RESULTS

This section provides detailed analysis of the proposed system. Simulation results are generated to confirm its' working principles. This chapter is segmented into two sections. In the first section, grid-connected PV system is designed and simulated. In the second section, a standalone PV system is also designed and simulated based on the energy requirement of Doko Township in Niger state of Nigeria. In both sections, PVsyst and HelioScope software are used separately.

Doko is a medium size community located in Niger State of Nigeria with a population of 171,672 and an average family size of 5 people. The geographical location of Doko is best determined by the longitudinal and latitudinal values of 5°58'0" E and 8°57'0" N accordingly. Previous electric power data from NEPA (national electric power authority) shows that an average of 4 kWh of electric power is consumed by each family and therefore the chosen PV power plant magnitude of 6 MW is large enough for the community; excess power will be exported to the grid. The PV plants are designed to accommodate the required energy at Doko during the period when the sun is out. Therefore, we can say the PV energy exported into the power grid (E_{inj}) shall be greater > than the amount of electricity procured by the grid system (E_{abs}) as mathematically given in the expression $E_{inj} > E_{abs}$.

4.1. Grid-Connected PV Design

This section provides system design and simulation results for the proposed gird-connected PV system. As mentioned above, two industry accepted software are used i.e., PVsyst and HelioScope. The proposed grid-connected PV system has a plant capacity of 6 MW. Figure 6 shows the plane tilt and plane orientation of the selected site in Doko township in Nigeria for building the proposed grid-tied PV system.

4.1.1. Grid PV Design Using PVsyst

Grid-connected PV systems mostly referred to as PV power plants are electrical installation that provide medium to high voltage for grid applications. Unlike conventional power plants that rely on generators of various magnitudes (kW or MW) to generate electric power, PV power plants do not utilize generators for electric power production. Rather, several hundred or thousands of solar panels are connected in strings for power generation. Because PV power plants depend on several components and factors such as weather condition at the plant location, the type of PV module and inverter and their specific efficiency, the total output power can vary from location to location. STC (standard test condition) provides a standardized criterion for evaluating the power output and efficiency of all PV modules, this data is available on the nameplates of all PV modules.

Most grid-connected PV systems do not require battery. It can be considered as economic benefit for reducing system cost. Equation (3) is essential for selecting PV modules (M_s). The M_c and M_η represent the module capacity and efficiency accordingly. M_p and M_a represent the module price and area respectively. The dc and ac power of the system are related by Equation (4).

The proposed PV power plant to be situated in Doko occupy an area of 30609m^2 for the solar panels/modules only. More spacing is required to demarcate the area and also provide space for mini-substation to appropriately condition the electric power for onward transmission. The number of modules required for the proposed 6 MW power plant is computed by Equations (5) and (6) where M_n, P_e, and W_p represent number of modules, estimated plant power and individual module power respectively. The number of inverters required is computed by Equations (7) and (8). The maximum or peak power (P_p) of the system is computed by Equation (9), where, P_d and S_R present the power consumed daily (kWh/d) and STC (kW/m^2) solar radiation, respectively, and G_{SR} and Inv_Y represent global solar radiation and inverter yield accordingly. The derating factor expressed by D_F.

$$M_s = \frac{M_c \times M_\eta}{M_p \times M_a} \tag{3}$$

$$P_{dc,STC} = \frac{P_{ac}}{Conversion\ Efficiency} \tag{4}$$

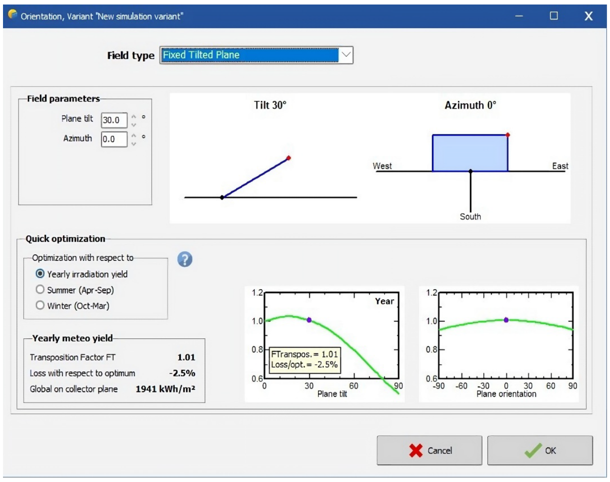
$$M_n = \frac{P_e}{W_p} \tag{5}$$

$$M_N = \frac{6\ \text{MW}}{330\ \text{W}} \approx 18183\ \text{modules} \tag{6}$$

$$\text{Inverter quantity} = \frac{\text{Estimated plant power}}{\text{Selected inverter power}} \tag{7}$$

$$\text{Inverter quantity} = \frac{6\ \text{MW}}{15\ \text{kW}} = 400\ \text{inverters} \tag{8}$$

$$P_p = \frac{P_d \times S_R}{G_{SR} \times D_F \times Inv_Y} \tag{9}$$



Orientation, Variant "New simulation variant"

Field type: Fixed Tilted Plane

Field parameters
Plane tilt: 30.0 °
Azimuth: 0.0 °

Quick optimization
Optimization with respect to
● Yearly irradiation yield
○ Summer (Apr-Sep)
○ Winter (Oct-Mar)

Yearly meteo yield
Transposition Factor FT: 1.01
Loss with respect to optimum: -2.5%
Global on collector plane: 1941 kWh/m²

FTranspos. = 1.01
Loss/opt. = -2.5%

Figure 6. Module orientation

The module arrangement is such that 19 modules are connected in series to form one string, therefore, there are 957 strings in the field arrangement. Each module has open circuit voltage of 44.7 V at -10°C and maximum power point voltage of 29.6 V at 60 °C. The peak power of each module is 330 Wp. Canadian solar inverter (15 kW, 160-850 V, 50 Hz) was selected to provide ac voltage for the grid, 400 of these inverters are required for the power plant. The selected solar inverter has 126 number of MPPT (maximum power point tracking) inputs therefore there's a total of 945 kW of inputs. The modules are at a fixed orientation with plane tilt and azimuth angles of 30° and 0°, respectively. The module orientation details are illustrated by Figure 6.

4.1.2. Grid PV (PVsyst) Simulation Results

PVsyst simulation of the proposed Doko PV power plant is done using a 22-year-old solar data recorded by NASA (National Aeronautical and Space Administration). Results of the proposed 6MW Doko PV power plants are illustrated by Figure 7 to Figure 11. Figure 7 shows the monthly energy or sunshine incident on the solar panels at Doko PV power plant site. From Figure 7, the months of January and December recorded the highest incident energy while June, July and August recorded the least incident energy. This is actually correct considering the weather forecast in the region. June, July and August are the raining season in the region and will therefore have the least sunshine duration and insolation. Figure 8 and Figure 9 shows the magnitude of electric power generated from the incident energy. Three distinct colors are used in indicating the amount of useful energy produced and the losses incurred by the modules and inverter.

Two types of losses are made during energy conversion i.e. collection losses which is caused by the modules and system losses which is caused by inverter and other auxiliary components. Figure 9 shows the monthly values in kWh/kWp/day while Figure 8 shows the same values in percentage terms. Figure 10 shows the performance ratio (PR) of the proposed Doko PV power plant. Performance ratio is considered as the efficiency estimator of PV systems [23-24]. PR values can be expressed in unity terms or percentage terms. The closer this value is to 1 in unity terms representation, the better the PV power plant. In percentage representation, the closer the value is to 100 the better the performance of the PV power plant. The result illustrated by Figure 10 shows that the PR value is 82.6% which considered high. Therefore, the proposed Doko PV power plant has high operating efficiency. Figure 11 illustrates the energy flow diagram for proposed Doko PV power plant from incident energy to grid injected energy.

1931 kW/m^2 global horizontal irradiation is incident on the modules; the modules generate 11.31 GWh of electric power from the incident energy. There are losses along the energy conversion chain, the final magnitude of energy produced at the inverter output is 9.60 GWh i.e. the grid injected voltage is 9.60 GWh. The above figures (Figure 7 to Figure 11) were obtained after simulation using PVsyst software. Table 2 to Table 5 were also generated by PVsyst and each one of them represent a specific system parameter.

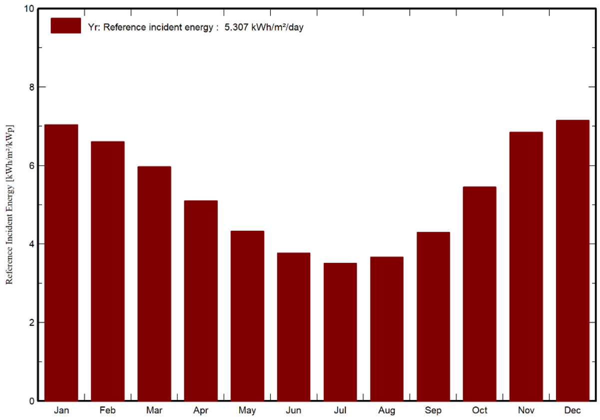


Figure 7. Reference incident energy in collector plane

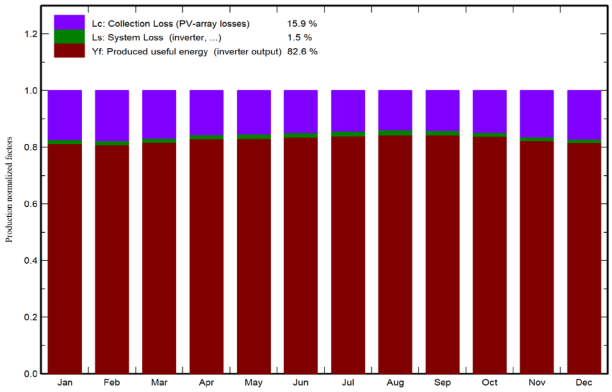


Figure 8. Monthly useful energy and losses

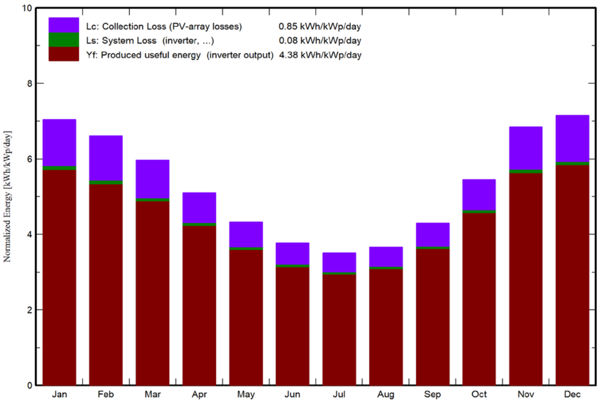


Figure 9. Monthly useful energy and losses production

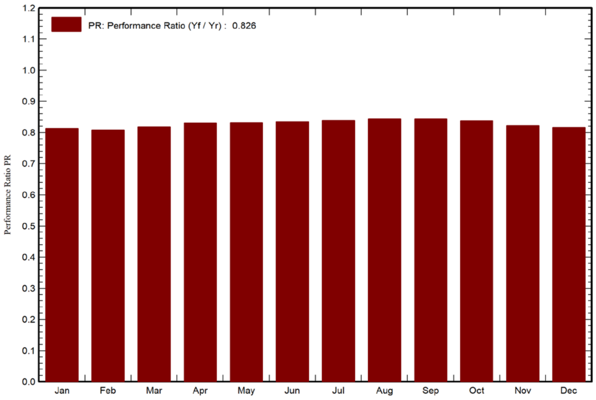


Figure 10. Monthly performance ratio values

Table 2. Balances and main results

Month	GlobHor kWh/m^2	DiffHor kWh/m^2	T_Amb °C	Globlnc kWh/m^2	GlobEff kWh/m^2	EArray kWh	E_Grid kWh	PR Ratio
January	177.9	46.50	27.14	218.2	214.5	1082456	1064564	0.813
February	165.5	49.28	27.51	185.0	181.8	913434	897782	0.809
March	186.3	62.62	26.93	185.1	180.9	924814	909014	0.818
April	173.4	66.00	26.29	153.2	148.4	776557	763417	0.831
May	168.3	66.96	25.86	134.3	128.8	682414	670069	0.832
June	147.6	64.80	24.94	113.1	107.8	578200	566851	0.835
July	137.6	68.51	24.09	108.9	104.0	560134	548671	0.840
August	132.1	70.68	24.00	113.7	109.5	587626	575797	0.844
September	136.5	68.10	24.40	129.0	125.2	664635	652819	0.844
October	158.7	62.93	24.73	169.2	165.5	865571	851221	0.839
November	171.6	47.10	25.40	205.5	201.8	1031559	1014960	0.823
December	175.8	43.40	26.41	221.8	218.1	1103851	1086537	0.816
Total	1931.3	716.88	25.63	1937.0	1886.4	9771250	9601703	0.826

Table 3. Incident energy

Month	GlobHor kWh/m^2	DiffHor kWh/m^2	T_Amb °C	WindVel m/s	Globlnc kWh/m^2	DifSlnc kWh/m^2	Alb_lnc kWh/m^2	DifS_Gl Ratio
January	177.9	46.50	27.14	0.0	218.2	23.27	2.384	0.0
February	165.5	49.28	27.51	0.0	185.0	22.02	2.217	0.0
March	186.3	62.62	26.93	0.0	185.1	27.30	2.496	0.0
April	173.4	66.00	26.29	0.0	153.2	29.84	2.320	0.0
May	168.3	66.96	25.86	0.0	134.3	32.28	2.251	0.0
June	147.6	64.80	24.94	0.0	113.1	34.02	1.975	0.0
July	137.6	68.51	24.09	0.0	108.9	39.78	1.842	0.0
August	132.1	70.68	24.00	0.0	113.7	40.47	1.768	0.0
September	136.5	68.10	24.40	0.0	129.0	37.43	1.826	0.0
October	158.7	62.93	24.73	0.0	169.2	31.76	2.125	0.0
November	171.6	47.10	25.40	0.0	205.5	22.89	2.299	0.0
December	175.8	43.40	26.41	0.0	221.8	22.32	2.354	0.0
Total	1931.3	716.88	25.63	0.0	1937.0	363.39	25.856	0.0

Table 4. Hourly energy supplied to the grid [MWh]

Month	0-5H	6H	7H	8H	9H	10H	11H	12H	13H	14H	15H	16H	17H	18-23H
January	0	17	55	92	122	140	147	144	130	107	73	36	1	0
February	0	9	34	68	102	126	135	133	118	91	56	24	1	0
March	0	11	41	76	108	128	137	129	114	87	55	23	1	0
April	0	13	40	70	94	108	106	103	94	74	45	17	0	0
May	0	12	38	64	82	95	97	95	79	61	36	12	0	0
June	0	8	28	50	70	79	84	78	69	54	33	12	1	0
July	0	7	27	47	62	75	77	77	70	54	37	15	1	0
August	0	9	29	50	65	77	81	78	71	59	39	17	1	0
September	0	16	42	65	81	94	87	87	73	57	37	14	0	0
October	0	24	54	81	102	115	118	113	101	78	48	18	0	0
November	0	32	67	100	122	134	148	133	119	92	58	23	0	0
December	0	30	66	102	128	144	148	143	128	102	66	31	0	0
Total	0	188	521	865	1337	1313	1354	1313	1166	915	583	243	6	0

Table 5. Detailed losses by inverter

Losses (kWh)	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total
InvLoss	18291	16808	15979	13140	12344	11349	11464	11829	11835	14353	16850	17806	172048
IL_Oper	17645	15489	15471	12778	12107	11123	11294	11624	11632	1887	16253	17128	166417
IL_P_{min}	97.5	26	175.9	210.2	81.7	78.6	16.9	51.8	28.2	314.7	194.8	26.2	1302.6
IL_P_{max}	379	1157	179	0	0	0	0	0	19	4	251	491	2501

Table 4 shows the hourly produced energy. It is evident that from 6:00 in the morning to 17:00 in the evening, the power plant is able to generate various magnitude of power at hourly intervals. Table 2 shows the monthly incident energy and the relative grid injected energy as well as the performance ratio of the proposed PV power plant. August and September produced the best PR value of 0.844. Table 3 shows the various weather conditions useful in solar PV applications. Table 5 shows detailed losses due to the inverter application.

4.1.3. Grid PV Design Using HelioScope

In this section, the proposed 6MW PV power plant is designed and simulated using HelioScope software. This will enable us to provide comparative analysis of the results generated by PVsyst and HelioScope. The same system components are utilized in both software i.e. the type of module and inverter are the same with respect to power ratings and manufacturer. Also, the plant location and size are the same.

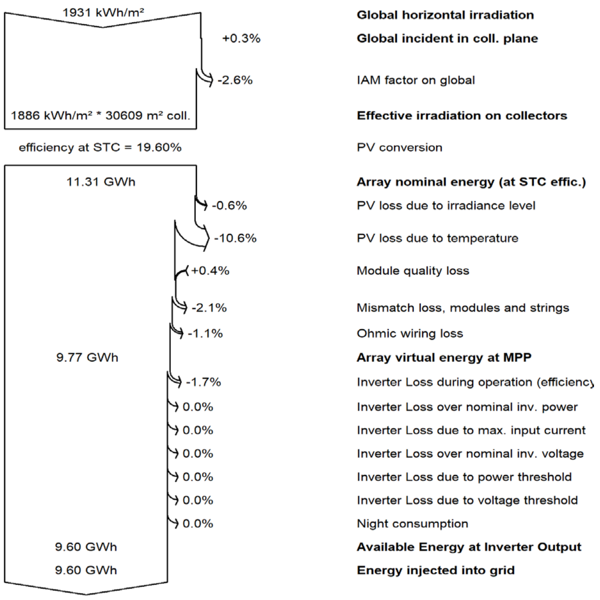


Figure 11. Loss-line diagram for Doko PV plant

Figure 15 shows the field arrangement of modules and inverters at the site location. A total of 18183 330 Wp Kioto modules and 400 15kW Canadian solar inverters are used. The string count, module quantity and technical details are illustrated by Figure 15. The monthly and annual energy production are expressed in Table 6 and Table 7 accordingly. The month of May recorded the highest output power with over 750 kWh power injected into the grid. The annual grid injected energy is 7.244 GWh. Figure 12 shows the overall system losses. For example, the inverter losses, mismatch losses and wiring losses are 3.4%, 3.5% and 0.4%, respectively.

Figures 13 and 14 shows the comparative analysis of the results obtained by PVsyst and HelioScope software for the proposed 6MW grid-tied PV system. Figure 13 shows the grid-injected power for both software. There is a sharp deviation in the curves at the beginning and at the end of the year for Figure 13. Nonetheless, the mid-year section has less deviation. Comparatively, PVsyst generates higher grid power compared to HelioScope. Figure 14 shows the performance ratio graph for PVsyst and HelioScope and its evident that PVsyst has better performance ratio compared to HelioScope.

Table 6. Monthly energy production

Month	GHI kWh/m^2	POA kWh/m^2	Shaded kWh/m^2	Nameplate kWh	Grid kwh
Jan	149.7	102.3	96.3	534,319.3	458,713.8
Feb	144.5	110.2	104.2	584,893.3	499,026.3
Mar	168.2	143.5	136.1	770,407.2	653,136.5
Apr	162.6	153.7	146.0	832,459.9	704,501.6
May	166.4	169.6	161.7	925,341.3	779,210.2
Jun	151.7	158.9	151.4	867,849.5	737,358.4
Jul	142.8	147.7	140.2	801,564,.1	689,197.0
Aug	140.6	137.0	129.5	737,470.9	638,644.8
Sept	141.1	125.4	118.7	673,146.2	578,850.2
Oct	162.6	128.6	121.8	684,954.1	587,945.3
Nov	158.9	108.4	102.4	568,239.7	487,154.3
Dec	148.3	96.9	91.1	502,461.9	430,834.0

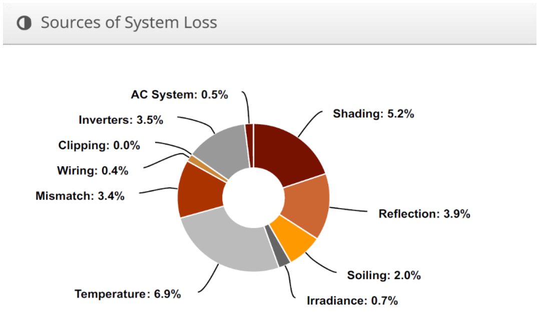


Figure 12. Detailed system losses

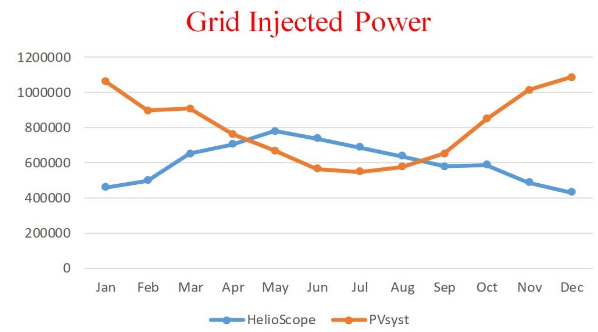


Figure 13. Comparative graph of grid injected power

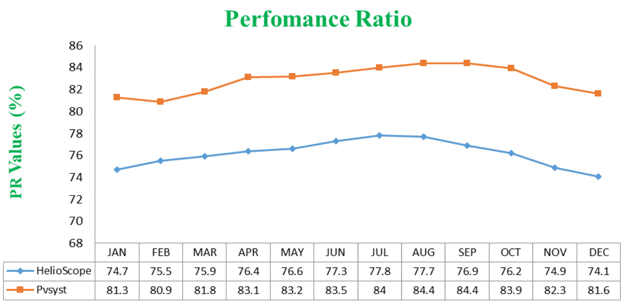


Figure 14. Comparative graph of monthly performance ratio value

Table 7. Detailed annual energy production

Annual production			
	Description	Output	Delta
Irradiance (kWhm^2)	Annual Global Horizontal Irradiance	1,837.5	
	POA Irradiance	1,582.2	-13.9%
	Shaded Irradiance	1,499.4	-5.2%
	Irradiance after Reflection	1,441.3	-3.9%
	Irradiance after Soiling	1,412.5	-2.0%
	Total Collector Irradiance	1,412.5	0.0%
Energy (kWh)	Nameplate	8,483,107.3	
	Output at irradiance levels	8,421,817.9	-0.7%
	Output at cell temperature Derate	7,842,176.6	-6.9%
	Output after mismatch	7,577,772.5	-3.4%
	Optimal DC output	7,545,091.1	-0.4%
	Constrained DC output	7,545,054.0	0.0%
	Inverter Output	7,280,977.0	-3.5%
	Energy to Grid	7,244,542.0	-0.5%
Temperature Metrics			
Average operating temperature		28.7 °C	
Average operating cell temperature		36.3 °C	
Simulation Metrics			
Operating Hours and		4622	
Solved Hours		4622	

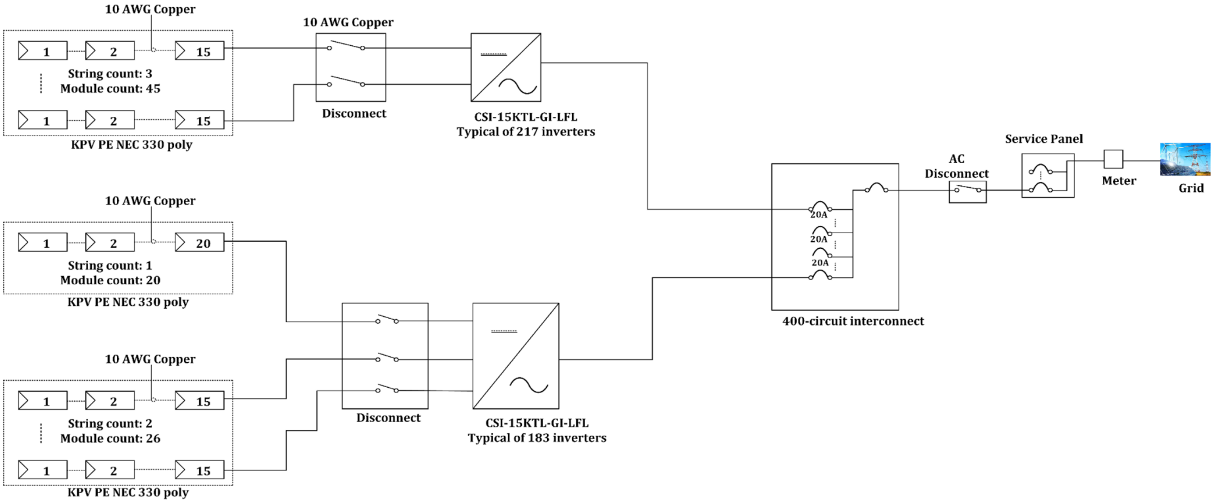


Figure 15. Module and inverter arrangement of the proposed power plant

4.2. Standalone PV Design

This section provides the design and simulation of a standalone PV system in Doko Township using HelioScope and PVsyst software. In HelioScope design, the maximum output power is based on the available area on the building rooftop. In PVsyst design, the maximum output power is based on the load and battery sizing calculations. According to [25], the average electricity consumption between urban and rural residents per month per person is 30 kWh and 17 kWh, respectively.

4.2.1. Standalone PV Design Using HelioScope

Two simulations are performed for the standalone system using HelioScope software. The two systems are chosen with respect to the biggest and smallest rooftops in Doko Township. The first system is rated at 75.4kW because it has the biggest rooftop area. 126 modules of 330Wp Kioto photovoltaics can occupy the available space on the rooftop. The number of inverters required for the system is 3 which are rated at 15 kW. The module and inverter distribution on the rooftop are similar to that of Figure 16. The second system is rated at 7.26 kW because it has the smallest rooftop area. 22 modules of 330 Wp Kioto photovoltaics can occupy the available space on the rooftop. The number of inverters required for the system is 1 which is rated at 15 kW. Figure 16 shows the module and inverter distribution on the rooftop for the second system. Based on the size of rooftops available in Doko, the biggest and smallest rooftops were selected as the areas for the standalone PV system implementation using HelioScope. The biggest and smallest rooftops have maximum capacity of 74.5 kW and 7.26 Kw, respectively. Table 8 and Table 9 shows the simulation output for the 74.5 kW rated standalone PV system. The monthly and annual energy production are expressed in Tables 8 and 9, respectively.

The system losses are indicated in Table 12. The simulation outputs of the smaller rooftop area are expressed in Table 10 and Table 11. The monthly and annual energy production are expressed by Tables 10 and 11, respectively. The system losses are indicated in Table 12.

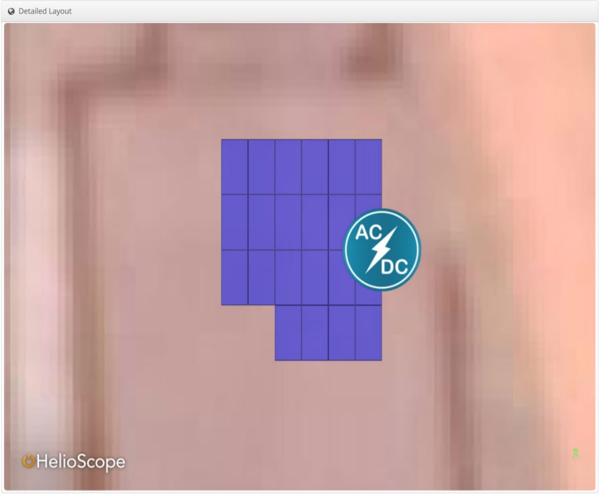


Figure 16. 7.26kW Standalone photovoltaic system

Table 8. Annual energy production for 75.4 kW

	Description	Output	Delta
Irradiance (kWhm^2)	Annual Global Horizontal Irradiance	1,837.5	
	POA Irradiance	1,791.0	-2.5%
	Shaded Irradiance	1,791.0	-0.0%
	Irradiance after Reflection	1,726.2	-3.6%
	Irradiance after Soiling	1,691.7	-2.0%
	Total Collector Irradiance	1,691.7	0.0%
Energy (kWh)	Nameplate	70,408.6	
	Output at irradiance levels	70,098.8	-0.4%
	Output at cell temperature Derate	60,114.6	-14.2%
	Output after mismatch	58,166.2	-3.2%
	Optimal DC output	58,086.6	-0.1%
	Constrained DC output	58,086.6	0.0%
	Inverter Output	56,053.4	-3.5%
	Energy to Grid	53,148.7	-5.2%
Temperature Metrics			
Average operating temperature		28.7ºC	
Average operating cell temperature		36.3ºC	
Simulation Metrics			
Operating Hours		4622	
Solved Hours		4622	

Table 9. Monthly energy production for 75.4 kW

Month	GHI	POA	Shaded	Nameplate	Grid
Jan	149.7	136.6	136.6	5,340.1	4,074.5
Feb	144.5	136.6	136.6	5,341.1	4,012.1
Mar	168.2	163.6	163.6	6,439.3	4,784.4
Apr	162.6	163.3	163.3	6,442.9	4,773.4
May	166.4	171.4	171.4	6,771.0	4,994.3
Jun	151.7	157.7	157.7	6,233.0	4,664.4
Jul	142.8	147.7	147.7	5,822.2	4,465.4
Aug	140.6	142.4	142.4	5,600.3	4,346.1
Sept	141.1	138.8	138.8	5,461.4	4,154.6
Oct	162.6	154.7	154.7	6,076.3	4,593.1
Nov	158.9	145.1	145.1	5,674.2	4,293.2
Dec	148.3	133.7	133.7	5,206.9	3,993.2

Table 10. Monthly energy production for 7.26 kW

Month	GHI kWh/m^2	POA kWh/m^2	Shaded kWh/m^2	Nameplate kWh	Grid kWh
Jan	149.7	136.6	136.6	932.4	748.8
Feb	144.5	136.6	136.6	932.5	740.4
Mar	168.2	163.6	163.6	1,124.3	884.8
Apr	162.6	163.3	163.3	1,124.3	884.9
May	166.4	171.4	171.4	1,182.2	925.0
Jun	151.7	157.7	157.7	1,088.2	862.5
Jul	142.8	147.7	147.7	1,016.5	823.7
Aug	140.6	142.4	142.4	977.8	801.2
Sept	141.1	138.8	138.8	953.5	766.3
Oct	162.6	154.7	154.7	1,060.9	847.7
Nov	158.9	145.1	145.1	990.7	790.4
Dec	148.3	133.7	133.7	909.1	732.1

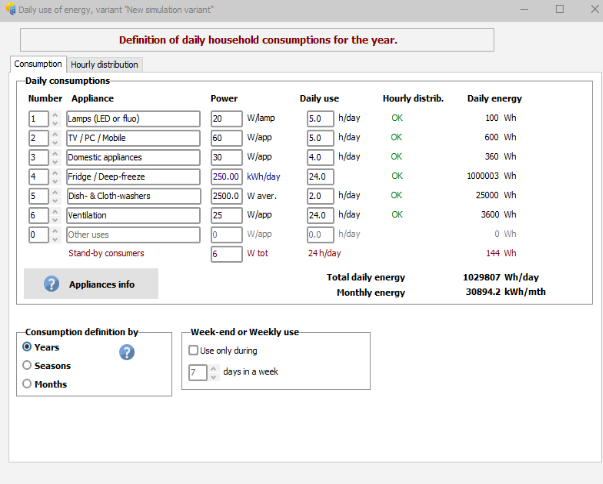
Table 11. Annual energy production for 7.26 kW

Annual production			
	Description	Output	Delta
Irradiance (kWhm^2)	Annual Global Horizontal Irradiance	1,837.5	
	POA Irradiance	1,791.0	-2.5%
	Shaded Irradiance	1,791.0	-0.0%
	Irradiance after Reflection	1,726.2	-3.6%
	Irradiance after Soiling	1,691.7	-2.0%
	Total Collector Irradiance	1,691.7	0.0%
Energy (kWh)	Nameplate	12,292.9	
	Output at irradiance levels	12,239.9	-0.4%
	Output at cell temperature Derate	10,496.0	-14.2%
	Output after mismatch	10,225.6	-2.6%
	Optimal DC output	10,214.8	-0.1%
	Constrained DC output	10,214.7	0.0%
	Inverter Output	9,857.2	-3.5%
	Energy to Grid	9,807.9	-0.5%
Temperature Metrics			
Average operating temperature		28.7°C	
Average operating cell temperature		36.3°C	
Simulation Metrics			
Operating Hours		4622	
Solved Hours		4622	

4.2.2. Standalone PV Design Using PVsyst

Unlike HelioScope, PVsyst does not rely only on the space available on the rooftop of the building but takes into consideration the energy needs of the family. Therefore, the energy requirement of the family needs to be entered into the software before simulation can be made. Figure 17 shows the home appliances and their respective rated power and duration of usage in hours for a day. Due to differences in pricing of electric energy during different hours of the day, the period of usage of the listed appliances of Figure 17 are illustrated in Figure 18.

Based on the hourly usage and distribution of electric power computed into PVsyst software, it was determined that an average of 10142 Wh of electric energy was required for a day and 30402.6 kWh of electric power was required for a month. Therefore, 76.2 kWp capacity of standalone PV systems was designed and simulated with PVsyst. 230 modules of Kioto photovoltaic rated 330Wp are used in an area of 431m^2. Simulation results of the 76.2 kWp system with energy saving components are illustrated by Figure 19 to Figure 23. The energy flow diagram of the proposed standalone photovoltaic systems is shown by Figure 23. 375.8 MWh of electric power is supplied to the user from an irradiance of 1931 kWh/m^2.


Daily use of energy, variant "New simulation variant"

Definition of daily household consumptions for the year.

Daily consumptions

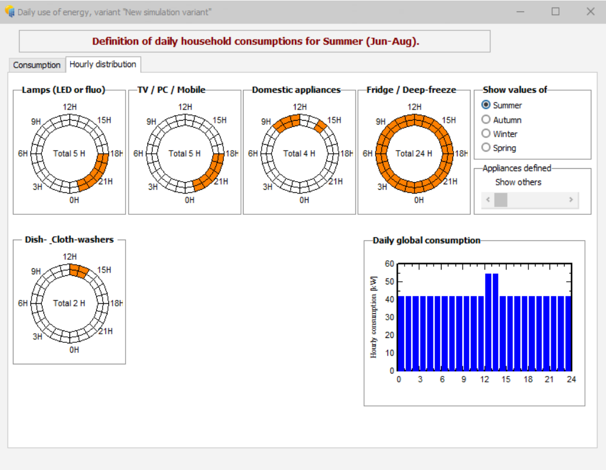
Number	Appliance	Power		Daily use		Hourly distrib.	Daily energy
1	Lamps (LED or fluo)	20	W/lamp	5.0	h/day	OK	100 Wh
2	TV / PC / Mobile	60	W/app	5.0	h/day	OK	600 Wh
3	Domestic appliances	30	W/app	4.0	h/day	OK	360 Wh
4	Fridge / Deep-freeze	250.00	kWh/day	24.0		OK	1000003 Wh
5	Dish- & Cloth-washers	2500.0	W aver.	2.0	h/day	OK	25000 Wh
6	Ventilation	25	W/app	24.0	h/day	OK	3600 Wh
0	Other uses	0	W/app	0.0	h/day		0 Wh
	Stand-by consumers	6	W tot	24 h/day			144 Wh

Total daily energy 1029807 Wh/day
Monthly energy 30894.2 kWh/mth

Consumption definition by
● Years
○ Seasons
○ Months

Week-end or Weekly use
☐ Use only during
7 days in a week

Figure 17. Hourly electric power consumption


Daily use of energy, variant "New simulation variant"

Definition of daily household consumptions for Summer (Jun-Aug).

Show values of
● Summer
○ Autumn
○ Winter
○ Spring

Figure 18. Hourly electric power usage distribution

Table 12. System losses

Parameter	7.26 kW System	75.4 kW System
	Losses (%)	Losses (%)
AC system	0.5	0.5
Inverters	3.5	3.5
Wiring	0.4	0.1
Clipping	0.0	0.0
Mismatch	3.4	2.6
Temperature	6.9	14.2
Shading	5.2	0.2
Reflection	3.9	3.6
Soiling	2.0	2.0
Irradiance	0.7	0.4

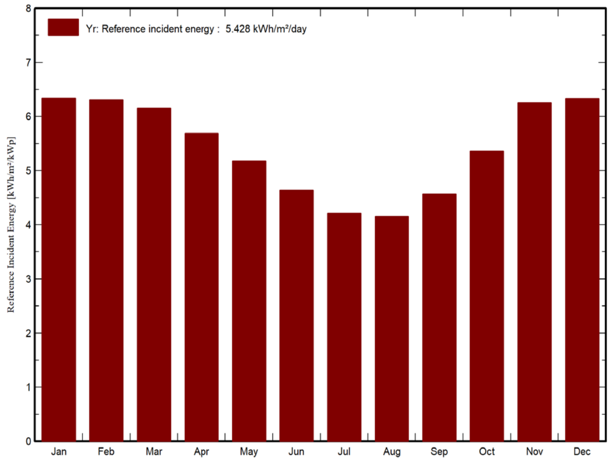


Figure 19. Reference incident energy in collector plane

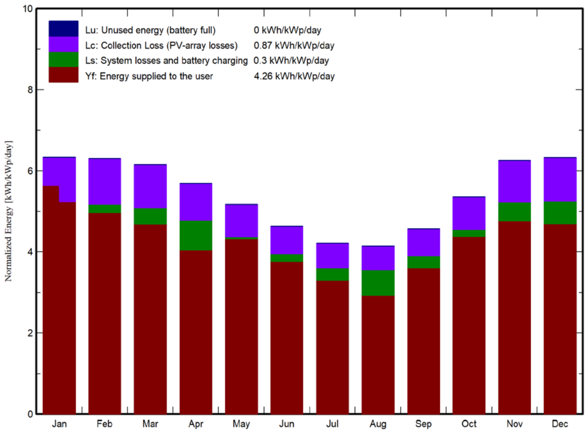


Figure 20. Monthly useful energy and losses production

Figure 19 shows the monthly incident energy on the modules. The average daily incident energy is 5.428 kWh/m^2.

The daily losses are represented by Figure 20 in kWh/m^2/day and Figure 21 in percentage. The losses due to collection is 0.87 kWh/m^2/day or 16%. The daily losses due to battery charging and system are 0.3 kWh/m^2/day or 5.5% and daily useful energy supplied is 4.26 kWh/m^2/day or 78.5%. Figure 22 shows the monthly values for performance ratio and solar fraction.

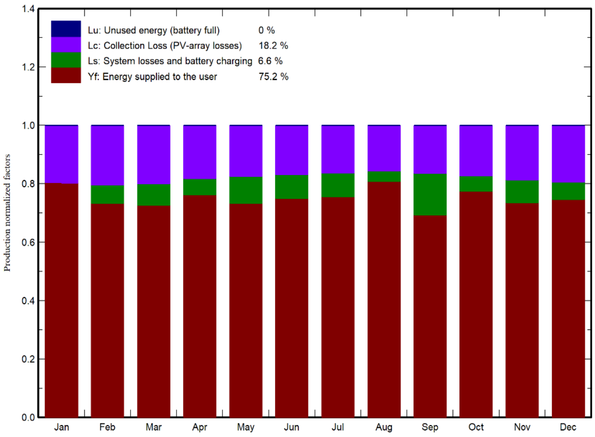


Figure 21. Monthly useful energy and losses production

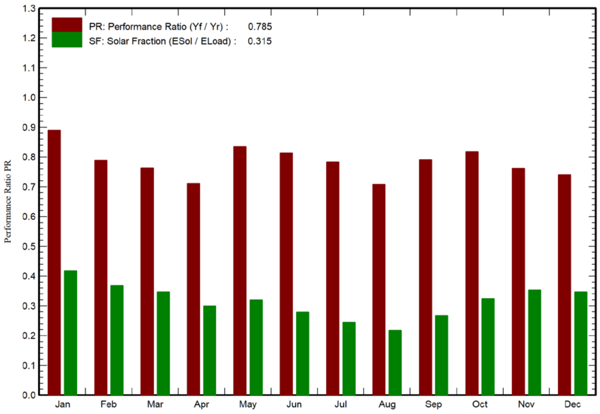


Figure 22. Performance ratio and solar fraction diagram

The cost of modules and inverters used for the grid connected and standalone systems are estimated and expressed in Table 13. A total of 18183 modules are used for the grid-connected system. Each module (330 Wp) cost 138$, therefore, the total cost of the modules is 2418339$. For the standalone system, the number of modules required are different. In the first HelioScope simulation, 126 modules are used at a cost of 16,758$. 22 modules are used in the second simulation at the cost of 2926$. 231 modules are used for PVsyst simulation at the cost of 30723$.

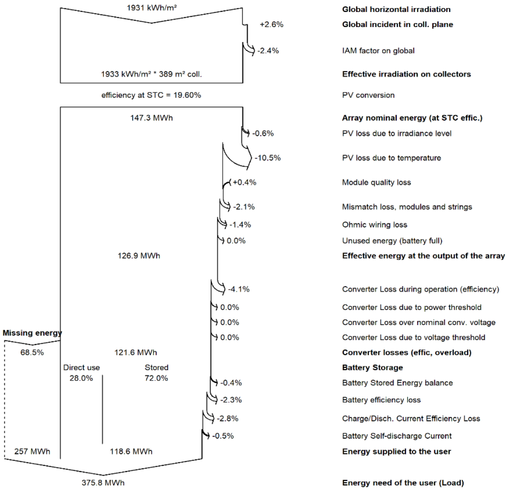


Figure 23. Loss-line diagram for Doko standalone PV plant

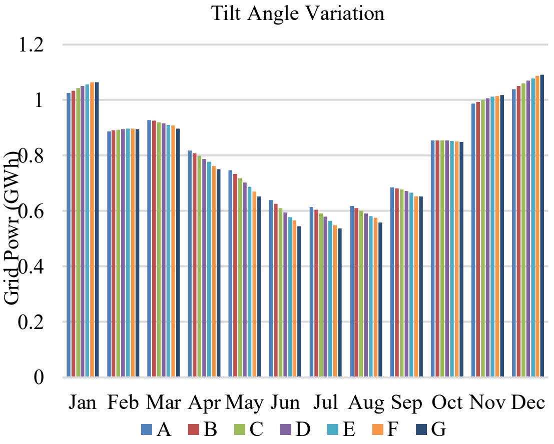


Figure 24. Grid power vs tilt angle variation

Table 13. Module and inverter cost estimation

	Grid-connected Systems				
Parameters	Module Type (W_p)	Number of Modules	Module Price $133	Number of Inverters	Inverter Price $458
HelioScope	330	18183	$2,418,339	400	$183,200
PVsyst	330	18183	$2,418,339	400	$183,200
	Standalone Systems				
HelioScope 1	330	126	$16,758	3	$1,374
HelioScope 2	330	22	$2,926	1	$458
PVsyst	330	231	$30,723	6	$2,748

5. CONCLUSIONS

This research proposed two photovoltaic systems for electric power generation. The generated power will be used in residential facilities and also for grid-connected applications. The viability of the proposed systems is determined by two highly rated, industry and academia accepted PV software known as PVsyst and HelioScope.

Both software uses real-time power plant location to determine the expected daily, monthly and yearly electric power output of the proposed plants. The location of the proposed PV power plant is Doko Township in Niger State of Nigeria. The grid-connected system is rated at 6MW. 18183 330 Wp Kioto modules tilted at 30° with 400 15 kW inverters were used for the grid-tied simulation. The output energy for the grid-tied simulations is 9.6 GWh and 7.244 GWh for PVsyst and HelioScope, respectively. Varying the tilt angle of the modules did not yield any significant change in the grid injected power. Figure 24 shows the graph of tilt angle variation from 22° represented by A to 32° represented by *G* with a step size of 2° i.e. the tilt angle of the modules was varied between 22°, 24°, 26°, 28°,30° and 32°.

For the standalone PV system, two systems were designed using HelioScope i.e. the largest and smallest rooftop areas were selected. The system with the biggest rooftop area is rated at 75.4 kW, 126 330 Wp modules, 3 15 kW inverters were used. Also, the system with the smallest rooftop area is rated 7.26 kW, 22 330Wp modules, 1 15 kW inverter is used. The yearly output power for the 75.4 kW and 7.26 kW systems are 53148.7kWh and 9807.9 kWh respectively. The PVsyst system based on the energy assessment of the facility is rated at 76.2kW. From the loss-line diagram of the system, 9758 kWh of power was provided for the end user i.e. injected into the grid. Future work of this paper will include the prediction and classification of solar PV power generation using artificial intelligence. Also, a system will be designed to compare the achieved results with artificial intelligence algorithms.

REFERENCES

[1] International Energy Agency, "Africa Energy Outlook", 2022.

[2] ECOWAS (Economic Community of West African States), "Monitoring Report on the Impacts of COVID-19 in West Africa, Economic Community of West Africa States", UN Economic Commission for Africa, World Food Programme, 2021.

[3] UNEP (2020), "Used Vehicles and the Environment", www.unep.org/resources/report/global-trade-used-vehicles-report.

[4] C.C. Okpalajiaku and S. Amadi, "Electricity Pricing in the NESI: How Effective has the MYTO 2015 Been?", 2021 IEEE PES/IAS PowerAfrica, pp. 1-4, Nairobi, Kenya, 2021.

[5] A.E. Airoboman, F.O. Adunola, H.A. Salihu, I.S. Fahim, M.A. Aderibigbe, "Electricity Pricing in an Emerging Deregulated Market: A Case of Nigeria and Egypt", The 6th IEEE International Energy Conference (ENERGYCon), Gammarth, pp. 797-801, Tunisia, 2020.

[6] Netherlands Enterprise Agency, "Sector Study, Solar Renewable Energy in Nigeria", May 2021.

[7] N. Hagumimana, J. Zheng, G. Norense, O. Asemota, J.D.D. Niyonteze, W. Nsengiyumva, A. Nduwamungu, S. Bimenyimana, "Concentrated Solar Power and Photovoltaic Systems: A New Approach to Boost Sustainable Energy for all (Se4all) in Rwanda", International Journal of Photoenergy, Article ID 5515513, p. 32, 2021.

[8] International Energy Agency, "Solar Energy Perspectives", 2020. www.eng.uc.edu/~beaucag/Classes/SolarPowerForAfrica/SolarEnergyPerspectives6111251e.pdf.

[9] I.S. Amiri, M. Ariannejad, "Introducing CTS (Copper-Tin-Sulphide) as a Solar Cell by Using Solar Cell Capacitance Simulator (SCAPS)", Springer, 2019.

[10] S.N. Tackie, O.C. Ozerdem, "Performance Evaluation and Viability Studies of Photovoltaic Power Plants in North Cyprus", International Journal of Renewable Energy Research, Vol. 12, No. 4, December 2022.

[11] B. Zhou, J. Pei, D.M. Nasir, J. Zhang, "A Review on Solar Pavement and Photovoltaic/Thermal (PV/T) System", Transportation Research Part D: Transport and Environment, Vol. 93, 2021,

[12] O.M. Abubakar, B.I. Adamu, "Comparative Study of Monocrystalline and Polycrystalline Silicon Solar Modules in Kebbi State Environment", International Journal of Scientific and Engineering Research, Vol. 10, No. 9, September 2019.

[13] K.E. Enongene. F.H. Abanda, I.J.J. Otene, S.I. Obi, C. Okafor, "The Potential of Solar Photovoltaic Systems for Residential Homes in Lagos City of Nigeria", Journal of Environmental Management, Vol. 244, pp. 244-256, August 2019.

[14] D.O. Johnson, A.A. Ogunseye, "Grid-Connected Photovoltaic System Design for Local Government Offices in Nigeria", Nigerian Journal of Technology, Vol. 36, No. 2, 2017.

[15] J.O. Oladigbolu, M.A.M. Ramli, Y.A. Al Turki, "Feasibility Study and Comparative Analysis of Hybrid Renewable Power System for Off-Grid Rural Electrification in a Typical Remote Village Located in Nigeria", IEEE Access, Vol. 8, pp. 171643-171663, 2020.
[16] R. Olarewaju, A.S. Ogunjuyigbe, T.R. Ayodele, A.A. Yusuff, "Performance Investigation of a Proposed 75MW Grid Connected Solar PV in Kankia, Nigeria", IEEE PES/IAS PowerAfrica, pp. 1-5, Nairobi, Kenya, 2020.
[17] E.C. Asiri, C.Y. Chung, X. Liang, "Day-Ahead Prediction of Distributed Regional-Scale Photovoltaic Power", IEEE Access, Vol. 11, pp. 27303-27316, 2023.
[18] J.O. Oladigbolu, M.A.M. Ramli, Y.A. Al Turki, "Feasibility Study and Comparative Analysis of Hybrid Renewable Power System for off-Grid Rural Electrification in a Typical Remote Village Located in Nigeria", IEEE Access, Vol. 8, pp. 171643-171663, 2020.
[19] O.T. Ibitoye, et al., "Nigeria Electricity Grid and the Potentials of Renewable Energy Integration: A Concise Review", The 7th International Energy Conference (ENERGYCON), pp. 1-4, Riga, Latvia, 2022.
[20] E.C. Asiri, C.Y. Chung, X. Liang, "Day-Ahead Prediction of Distributed Regional-Scale Photovoltaic Power", IEEE Access, Vol. 11, pp. 27303-27316, 2023.
[21] Y.O.N. Udoakah, E.E. Nta, I.E. Okon, U.E. Akpabio, "Design of a 1 KVA PV System for Electrical Laboratory in Faculty of Engineering, University of UYO, Nigeria", IEEE Global Humanitarian Technology Conference (GHTC 2014), pp. 1-5, San Jose, CA, USA, 2014.
[22] A.S. Oladeji, M.F. Akorede, "Assessment of Solar and Hydropower Energy Potentials of Three Rural Communities in Nigeria", IEEE PES/IAS PowerAfrica, pp. 187-192, Abuja, Nigeria, 2019.
[23] O.C. Ozerdem, S. Tackie, S. Biricik, "Performance Evaluation of Serhatkoy (1.2 MW) PV Power Plant", The 9th International Conference on Electrical and Electronics Engineering (ELECO), pp. 398-402, Bursa, Turkey, 2015.
[24] S.N. Tackie, B.K. Kurehwatira, "Switched Inductor Capacitor Based DC-AC Converter for PV Applications", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 50, Vol. 14, No. 1, pp. 238-246, March 2022.
[25] K. Olaniyan, C. Benjamin, S.O. McLellan, T. Tetsuo, "Estimating Residential Electricity Consumption in Nigeria to Support Energy Transitions", Sustainability, Vol. 10, No. 5, p. 1440, 2018.
[26] Solargis, "Global Horizontal Irradiation Map of Nigeria", 2023.

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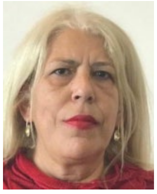

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