

Comparative Analysis of the Solar Potential of Offshore and Onshore Photovoltaic Power System

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Abstract

In this paper, comparative analyses of performance parameters of onshore and offshore PV system are conducted and the result showed that the offshore PV system has better performance in terms of higher energy yield and performance ratio as well as improved temperature de-rating factor due to its lower cell temperature. The study is conducted for PV array site around Bar Beach in Lagos, Nigeria. Meteorological data from NASA website and PV array with total area of 268m² are used for the study. According to the results, the offshore ambient temperature is about 5.57% less than that of onshore, the offshore wind speed is 74.86% more than that of the onshore, whereas, the offshore effective PV cell temperature is 9.96% less than that of the onshore. The cumulative effect of the differences in atmospheric parameters on the PV cell temperature also resulted to 1.99% higher and better offshore de-rating factor over that of the onshore as well as 1.99% improvement in energy output, the specific energy yield and performance ratio. Evidently, the offshore PV with lower effective cell temperature performed better than the onshore PV system.

Keywords: Photovoltaic; Standalone PV System; Cell Temperature; Temperature De-rating factor; Onshore PV System; Offshore PV System.

1. Introduction

Over the years, solar energy has become a very important source of energy all over the world, more especially in developing countries such as Nigeria [1]. Furthermore, in Nigeria, due to the perennial severe shortfall in energy supply from the national grid, most residential and commercial consumers are resorting to alternative forms of energy to meet their energy demands [2]. In this wise, photovoltaic (PV) energy system has become the best choice for alternative energy source for Nigerian energy consumers given the abundant solar radiations that are readily available all over the country, all year round.

In addition, in recent years, the added advantages of lower cell temperature of water-cooled or floating PV systems have gained much attention of researchers [3,4]. However, Nigerians are yet to key into such advancement in PV power technology. Particularly, most tourist centers by seashores are still powered by diesel generators despite the higher solar energy potential that the sea climate with lower ambient

temperature can afford for PV power installation [5,6,7] In view of this oversight, this paper seeks to examine the performance of PV installation on seashore of Bar Beach in Lagos state of Nigeria and then compare the performance with that of offshore PV installation.

According to studies, PV power plants' performance depends on numerous parameters that amount to many loss mechanisms [8,9,10]. Notably, the specific losses associated with a given PV plant can be categorized into two groups, namely, system losses and capture losses. Capture losses are caused by factors such as attenuation of the incoming light, soiling of PV module surface, ambient temperature, electrical mismatching, among others [9, 11]. For instance, module output power reduces as module temperature increases. Dirt and dust that do accumulate on the PV module surface block some of the sunlight reaching the module and thereby reduce the module output power.

On the other hand, system losses are caused by factors such as wiring losses, inverter inefficiency losses and transformer conversion losses [9,11]. For example, the inverters used in most PV systems have peak efficiencies that are less than 100%. Consequently, some of the DC power generated by the PV modules is lost in the DC to AC conversion process. The cumulative effect of all the losses are captured as de-rating factor used to reduce the STC rated power of the PV module to the actual value that is dependent on the particular system components and environmental factors for the given PV installation. As such, in order to compare different PV installations some performance parameters that capture some or all of the system and environmental factors are required [10,12]. Among others, the three most commonly used parameters are the yearly energy output of the PV installation, the specific energy yield and the performance ratio plant [13,14,15,16,17,18,19].

One common basis for comparing PV modules is through the use of Standard Test Condition (STC) in specifying PV parameters; where the STC is given as 1000 W/m^2 Irradiance, 25°C cell temperature, and AM1.5 Spectrum [20,21,22,23]. In particular, manufacturers often specify the peak power (W_p) output of a PV panel. The peak power value specifies the output power achieved by a PV module under Standard Test Conditions with peak solar radiation of $1,000 \text{ m}^2$. In practice, the maximum power a PV installation can produce will usually be significantly lower than the peak power rating. One reason for this is that peak solar radiation of $1,000 \text{ m}^2$ is a high level of solar radiation achieved only in very sunny conditions. The actual solar radiation received in most cases will often be less than the peak solar radiation figure and will also be dependent on other system losses and capture losses associated with the PV installation. Essentially, in most PV installations, the actual energy output of the PV is less than the rated peak energy output of the PV. The ratio of the actual power output to the peak power output is known as the performance ratio. The performance ratio (PR) is usually expressed in percentage. PR refers to the ratio of the actual energy output and the theoretical energy output of the PV [24]. Hence, PR shows the percentage of the energy that is actually delivered to the load after subtracting the energy loss due to various system and capture losses associated with the PV installation.

Another key PV performance parameter considered in this paper is the specific energy yield. The specific energy yield is the net energy output divided by the nameplate DC power at the standard test condition (STC) of an installed PV array [25,26,27]. It represents the number of hours the PV array would need to operate at its rated power or peak rating to provide the same energy. The units are hours or kWh/kWp. The three key performance parameters, namely, yearly energy output of the PV installation, the specific energy yield and the performance ratio are used in this paper to compare the

performance of offshore and onshore PV installations sited around Bar Beach in Lagos state, Nigeria. The aim is to demonstrate the benefit of siting PV installation around the beach with it lower ambient temperature and higher wind speed when compared to the onshore environment.

2. Description of the Case Study, Lagos Bar Beach

Lagos is Nigeria's commercial capital, as well as the second most populous and second fastest-growing city in Africa and the seventh fastest-growing city in the world [28,29]. Lagos Bar Beach is the main (inner city) beach, the most accessible and most visited beach in Lagos. At latitude of 6.422290° and longitude of 3.411700, Bar Beach is located in Victoria Island which is an affluent business and residential area in Lagos Island of Lagos state. The beach runs from the west by the Institute of Oceanography all the way to Eko Hotel toward the east. Bar Beach is named after the sand bars that characterized the Lagos Atlantic Ocean coastline which stretch up to 100 kilometres [30]. Due to large influx of tourist, the beach is lined with numerous shops and recreational facilities. Also, there are several hotels sited all around the beach.

3. Methodology and Algorithms

3.1. Methodology

In this study, among other things, the output energy, the specific energy yield and the performance ratio of offshore and onshore PV array located at around Lagos Bar Beach are determined. The study is based on meteorological data obtained from NASA website and PV array that consists of Schott ASE-260-DG-FT/250W PV modules with total array area of 268m².

3.2 Meteorological Data for Lagos Bar Beach

3.2.1. Onshore Meteorological Data for Bar Beach Lagos

Lagos Bar Beach is located at latitude of 6.422290° and longitude of 3.411700°. Hence, from NASA website, onshore meteorological data for the given latitude and longitude are used for the study. The meteorological data, in Table 1, include the monthly averaged daily insolation incident on a horizontal surface, the monthly averaged daily insolation incident on an equator-pointed optimally tilted surface, the daily mean air temperature, and the monthly averaged wind speed at 10 m above the sea level. Generally, solar irradiation is provided as kWh/m². However, it can be stated as daily Peak Sun Hours (PSH) [31]. This is the equivalent number of hours of solar irradiance of 1 kWh/m². Hence, in Table 1, solar irradiations (H_T and H_H) of say 5 kWh/m²/day is equivalent to 5h in PSH.

3.2.2. Offshore Meteorological Data for Bar Beach Lagos

(i) **Offshore Ambient Temperature in °C (T_w):** The offshore (or sea) ambient temperature (T_w) is related to the onshore (or land) ambient temperature (T_a) as follows [31,32]:

$$T_w = 5.0 + 0.75(T_a) \quad (1)$$

From Table 1, the annual average onshore ambient temperature (T_a) is 25.74°C, then the annual average offshore ambient temperature (T_w) is given as;

$$T_w = 5.0 + 0.75 * 25.74 = 24.305^\circ\text{C}$$

(ii) **Offshore Wind Speed in m/s (V_{ww}):** The offshore (or sea) wind speed (V_{ww}) is related to the onshore (or land) wind speed (V_{wa}) as follows [34,35,36]:

$$V_{ww} = 1.62 + 1.17(V_{wa}) \quad (2)$$

From Table 1, the annual average onshore wind speed (V_{wa}) is 2.8 (m/s), then the annual average offshore wind speed (V_{ww}) is given as;

$$V_{ww} = 1.62 + 1.17(2.8) = 4.896(m/s)$$

Table 1: The 22-year average onshore meteorological data for Bar Beach Lagos located at latitude of 6.422290° and longitude of 3.411700°.

Month	Monthly Averaged Daily Insolation Incident On A Horizontal Surface (kWh/m ² /day)	Monthly Averaged Daily Insolation Incident On An Equator-Pointed Tilted Surface, At Tilt Angle Of 15.5° (kWh/m ² /day)	The Daily Mean Air Temperature (°C)	Monthly Averaged Wind Speed At 10 m Above The Sea Level (m/s)
	H _H	H _T	T _a	V _{wa}
Jan	5.28	5.87	26.1	3.28
Feb	5.49	5.71	26.6	3.4
Mar	5.46	5.43	26.5	3.17
Apr	5.21	5.14	26.6	2.76
May	4.76	4.75	26.5	2.37
Jun	4.04	4.04	25.7	2.46
Jul	3.95	3.94	24.8	2.92
Aug	3.98	3.93	24.5	3.06
Sep	4.09	4.04	24.8	2.77
Oct	4.55	4.61	25.2	2.24
Nov	4.95	5.35	25.7	2.41
Dec	5.17	5.88	26	2.88
Annual	4.74	4.89	25.74	2.8

(Source: NASA website at: <https://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi> and https://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi?&num=184097&lat=6.422&submit=Submit&hgt=100&veg=17&sitelev=&email=&p=grid_id&p=ret_tlt0&p=T10M&p=wspd10arpt&step=2&lon=3.412)

3.3. PV Cell Temperatures for Lagos Bar Beach

Onshore Cell Temperature: The onshore PV cell temperature (T_{ca}) is given as follows [37]:

$$T_{ca} = 0.943 * T_a + 0.095 * G - 1.528 * V_{wa} + 0.3529 \quad (3)$$

Where;

G is the daily or monthly or yearly average insolation. In this paper, G is the daily insolation incident on a tilted surface (H_T) which the annual average has been determined in table 1 as 4.89kWh/m²/day or 4.89h in terms of PSH. Also, from table 1, the annual average onshore (or land) ambient temperature (T_a) is 25.74°C and the onshore (or land) wind speed temperature (V_{wa}) is 2.8m/s, hence,

$$T_{ca} = 0.943 * 25.74 + 0.095 * 4.89 - 1.528 * 2.8 + 0.3529$$

$$T_{ca} = 20.8061°C$$

Offshore Cell Temperature: The offshore floating PV cell temperature (T_{cw}) is given

as follows [37]:

$$T_{cw} = 0.943 * T_w + 0.095 * G - 1.528 * V_{ww} + 0.3529 \quad (4)$$

Where;

G is the daily or monthly or yearly average insulation. Again, G in this paper is 4.89kWh/m²/day or 4.89h in terms of PSH. Also, from table 1, the annual average offshore (or sea ambient temperature (T_w)) is 24.305°C and the offshore (or sea) wind speed temperature (V_{ww}) is 4.896m/s.

$$T_{cw} = 0.943 * 24.305 + 0.095 * 4.89 - 1.528 * 4.896 + 0.3529$$

$$T_{cw} = 16.24525^\circ\text{C}$$

3.4. PV Cell De-Rating Factors for Lagos Bar Beach

3.4.1. Onshore PV Cell Temperature De-rating Factor

The general expression relating the PV cell temperature and the PV cell temperature de-rating factor is given as follows [38]:

$$f_{temp} = 1 - (\alpha(T_{cell,eff} - T_{STC})) \quad (5)$$

Where

α is the power temperature coefficients; 0.40%/°C for the selected PV module

$T_{cell,eff}$ is the effective average daily cell temperature, where;

$$T_{cell,eff} = T_{c\ day} + T_{STC} = T_{ca} + T_{STC} \quad (6)$$

Generally, $T_{STC} = 25^\circ\text{C}$. Hence, for the onshore, $T_{cell,eff}$ is represented as $T_{cell,eff(a)}$ and the PV cell temperature de-rating factor represented as $f_{temp(a)}$ is given as;

$$T_{cell,eff(a)} = T_{c\ day} + T_{STC} = T_{ca} + T_{STC} \quad (7)$$

$$T_{cell,eff(a)} = 20.8061 + 25 = 45.8061^\circ\text{C}$$

$$f_{temp(a)} = 1 - (\alpha(T_{cell,eff(a)} - T_{STC})) = 1 - (\alpha(T_{ca} + T_{STC} - T_{STC})) \quad (8)$$

$$f_{temp(a)} = 1 - \alpha(T_{ca}) \quad (9)$$

Where, α must be divided by 100 if is given in %.

$$f_{temp(a)} = 1 - \frac{0.40}{100}(20.8061) = 0.9167756$$

3.4.2. Offshore PV Cell Temperature De-rating Factor

Similarly, for the offshore, $T_{cell,eff}$ is represented as $T_{cell,eff(w)}$ and the PV cell temperature de-rating factor represented as $f_{temp(w)}$, where

$$T_{cell,eff(w)} = T_{c\ day} + T_{STC} = T_{cw} + T_{STC} \quad (10)$$

$$T_{cell,eff(w)} = 16.24525 + 25 = 41.24525^\circ\text{C}$$

For the offshore, the PV cell temperature de-rating factor represented as $f_{temp(w)}$ is given as follows;

$$f_{temp(w)} = 1 - (\alpha(T_{cell,eff(w)} - T_{STC})) = 1 - (\alpha(T_{cw} + T_{STC} - T_{STC})) \quad (11)$$

$$f_{temp(w)} = 1 - \alpha(T_{cw}) \quad (12)$$

Where, α must be divided by 100 if is given in %.

$$f_{\text{temp}(w)} = 1 - \frac{0.40}{100}(16.24525) = 0.935019$$

3.4.3. The DC to AC De-Rate Factor ($f_{dc/ac}$)

Apart from cell temperature, there are other factors that reduces the conversion efficiency of the PV panels. The factors lead to greater reduction in the AC power delivered at the inverter output of the PV power supply system. Specifically, the cumulative effect of the all the factors that affects the overall DC to AC conversion efficiency of the PV power supply system are captured as DC to AC De-rate Factor . The array DC power rating is multiplied by an overall DC to AC de-rate factor to determine the AC power rating. The overall DC to AC de-rate factor accounts for losses from the DC nameplate power rating and is the mathematical product of the de-rate factors for the components of the PV system. A list of the standard de-rate factors and their typical values are presented in Table 3.

Table 2: De-rate Factors for AC Power Rating at STC (source: [39]).

Component De-rate Factors	PVWATTS Default	Range
PV module nameplate DC rating	0.95	0.80 - 1.05
Inverter and Transformer	0.92	0.88 - 0.98
Mismatch	0.98	0.97 - 0.995
Diodes and connections	0.995	0.99 - 0.997
DC wiring	0.98	0.97 - 0.99
AC wiring	0.99	0.98 - 0.993
Soiling	0.95	0.30 - 0.995
System availability	0.98	0.00 - 0.995
Shading	1.00	0.00 - 1.00
Sun -tracking	1.00	0.95 - 1.00
Age	1.00	0.70 - 1.00
Overall DC-to-AC de-rate factor	0.77	

Based on Table 2, the various de-rate factors are:

f_{pvtol} = de-rating factor due to PV module nameplate tolerance DC rating. The de-rate factor for the PV module nameplate DC rating accounts for the accuracy of the manufacturer's nameplate rating.

f_{inv} = de-rating factor due to Inverter and Transformer

f_{mism} = de-rating factor due to Mismatch

f_{diode} = de-rating factor due to Diodes and connections

$f_{dcwiring}$ = de-rating factor due to DC wiring

$f_{pacwiring}$ = de-rating factor due to AC wiring

$f_{soiling}$ = de-rating factor due to Soiling

$f_{sysavail}$ = de-rating factor due to System availability

- $f_{shading}$ = de-rating factor due to Shading
- $f_{suntrack}$ = de-rating factor due to Sun -tracking
- f_{aging} = de-rating factor due to Age
- $f_{dc/ac}$ = DC to AC de-rating factor

The overall DC to AC de-rate factor is calculated by multiplying the component de-rate factors. $f_{dc/ac} = f_{pvtol} * f_{mism} * f_{diode} * f_{dcwiring} * f_{pacwiring} * f_{soiling} * f_{sysavail} * f_{shading} * f_{suntrack} * f_{aging}$ (13)

Hence, for the default values in column 2 of table 2 gives:

$$f_{dc/ac} = 0.95 \times 0.92 \times 0.98 \times 0.995 \times 0.98 \times 0.99 \times 0.95 \times 0.98 \times 1 \times 1 \times 1 = 0.77$$

The value of 0.77 means that the AC power rating at STC is 77% of the nameplate DC power rating. In most cases, the overall default value of 0.77 will provide a reasonable estimate for modelling the energy production.

In all, $f_{dc/ac}$ includes de-rating due to manufacturer’s tolerances and de-rating due to dirt along with other relevant de-rating factors except the temperature de-rating factor.

3.5. Selection of PV Module

In this paper, the PV module selected is the Schott, ASE-260-DGFT/250W polycrystalline silicon PV module manufactured by Schott Solar with nominal power of 250Wp at STC, nominal voltage of 48V, manufacturers tolerance of ± 5%, efficiency of 11.72%, temperature coefficient of -0.47%/°C and cell area of 2.144 m² as shown in Figure 1.

PVSYST V5.20					11/05/16 06h01
BARBEACH PV MODULEDATA1					
Characteristics of a PV module					
Manufacturer, model :		Schott, ASE-260-DG-FT/250W			
Availability :		Prod. from2004 to 2007			
Data source :		Photon Mag. 2005			
STC power (manufacturer)	Pnom	250 Wp	Technology	Si-poly	
Module size (W x L)	1.336 x 1.605 m ²		Rough module area	Amodule	2.14 m ²
Number of cells	1 x 120		Sensitive area (cells)	Acells	N/A m ²
Specifications for the model (manufacturer or measurement data)					
Reference temperature	TRef	25 °C	Reference irradiance	GRef	1000 W/m ²
Open circuit voltage	Voc	70.4 V	Short-circuit current	Isc	4.80 A
Max. power point voltage	Vmpp	57.1 V	Max. power point current	Impp	4.40 A
=> maximum power	Pmpp	251.2 W	Isc temperature coefficient	mulsc	4.8 mA/°C
One-diode model parameters					
Shunt resistance	Rshunt	700 ohm	Diode saturation current	IoRef	211 nA
Serie resistance	Rserie	0.48 ohm	Voc temp. coefficient	MuVoc	-252 mV/°C
			Diode quality factor	Gamma	1.35
Reverse Bias Parameters, for use in behaviour of PV arrays under partial shadings or mismatch					
Reverse characteristics (dark)	BRev	3.20 mA/V ²	(quadratic factor (per cell))		
Number of by-pass diodes per module		6	Direct voltage of by-pass diodes		-0.7 V
Model results for standard conditions (STC: T=25°C, G=1000 W/m², AM=1.5)					
Max. power point voltage	Vmpp	57.2 V	Max. power point current	Impp	4.40 A
Maximum power	Pmpp	251.3 Wc	Power temper. coefficient	muPmpp	-0.40 %/°C
Efficiency(/ Module area)	Eff_mod	11.7 %	Fill factor	FF	0.744
Efficiency(/ Cells area)	Eff_cells	N/A %			

Figure 1: The Manufacturer Specifications For The Selected PV Module in the Study (Source: [40,41,42]).

3.6. Determination of the Daily Energy Output of the PV Array

In this paper, the total energy is determined based on a specified available space (area) for the PV array. Particularly, the specified available total area for all the PV modules is $268m^2$.

Let N_{PV} be the number of PV modules in the array;
let A_{PV} be the area of one PV module and let
 $A_{PVTOTAL}$ be the total area of all the PV modules. Then;

$$\text{Number of PV modules, } (N_{PV}) = \frac{\text{total area of all the PV modules}}{\text{area of one PV module}} = \frac{A_{PVTOTAL}}{A_{PV}} \quad (14)$$

$A_{PVTOTAL} = 268m^2$ and for the selected PV module, $A_{PV} = 2.144m^2$. Therefore,

$$N_{PV} = \frac{268}{2.14} = 125$$

3.6.1. The De-Rated Output Power of The Onshore PV Modules

The de-rated output power of the onshore PV modules can be determine as follows [43]:

Let $W_{PV_DR(a)}$ be the de-rated output power of the onshore PV modules and let W_{PV} be the module power at $STC = 250W_p$. Then,

$$W_{PV_DR(a)} = (W_{PV})(f_{dc/ac})(f_{temp(a)}) \quad (15)$$

Also, $f_{dc/ac}$ is the DC to AC de-rating factor which is given as 0.77 and $f_{temp(a)}$ is the onshore temperature de-rating factor which has a value of 0.9167756. Then,

$$W_{PV_DR(a)} = (250)(0.77)(0.9167756) = 176.479303$$

3.6.2. The Daily Energy Output From the Onshore PV Modules

Let $E_{PV_D_TOTAL(a)}$ be the daily energy output from the onshore PV modules, then;

$$E_{PV_D_TOTAL(a)} = (W_{PV_DR(a)})(N_{PV})(H_T) \quad (16)$$

Where;

$W_{PV_DR(a)}$ is the de-rated output power of the onshore PV modules
=176.479303

N_{PV} is the number of modules = 125

H_T is the irradiation for the tilt and azimuth angle of the array = $4.89 \text{ kWh}/m^2/\text{day}$ = 4.89h in terms of PSH. Hence,

$$E_{PV_D_TOTAL(a)} = (176.479303)(125)(4.89) = 107872.97 \text{ Wh}$$

$$E_{PV_D_TOTAL(a)} = 107.87297 \text{ kWh}$$

3.6.3. The De-Rated Output Power of the Offshore PV Modules

Similarly, the de-rated output power of the offshore PV modules can be determine as follows [43]:

$$W_{PV_DR(w)} = (W_{PV})(f_{dc/ac})(f_{temp(w)}) \quad (17)$$

where

$W_{PV_DR(w)}$ is the de-rated output power of the offshore PV modules

W_{PV} is the module power at STC = $250W_p$

$f_{ac/ac}$ is the DC to AC de-rating factor = 0.77

$f_{temp(w)}$ is the offshore temperature de-rating factor = 0.935019

$$W_{PV_DR(w)} = (250) (0.77) (0.935019) = 179.9911575$$

3.6.4. The Daily Energy Output From the offshore PV modules

$$E_{PV_D_TOTAL(w)} = (W_{PV_DR(w)}) (N_{PV})(H_T) \quad (18)$$

where

$E_{PV_D_TOTAL(w)}$ is the daily energy output from the offshore PV modules

$W_{PV_DR(w)}$ is the de-rated output power of the offshore PV modules
= 179.9911575

N_{PV} is the number of modules = 125

H_T is the irradiation for the tilt and azimuth angle of the array = $4.89 \text{ kWh}/\text{m}^2/\text{day}$
 $H_T = 4.89\text{h}$ in terms of PSH. Hence,

$$E_{PV_D_TOTAL(w)} = (179.9911575) (125)(4.89)$$

$$E_{PV_D_TOTAL(w)} = 110019.60\text{Wh} = 110.01960\text{kWh}$$

3.7. Determination of the Specific Energy Yield of the PV Array

The total rated power of the array at STC is W_{Array_STC} where [43];

$$W_{Array_STC} = (W_{PV}) \times (N_{PV}) \quad (19)$$

W_{PV} is the module power at STC = $250W_p$

N_{PV} is the number of modules = 125

Therefore,

$$W_{Array_STC} = (250) \times (125) = 31250 \text{ Wp} = 31.250 \text{ kWp}$$

3.7.1. The Specific Energy Yield for the Onshore PV Array

The actual yearly energy output from the onshore PV modules is given as;

$$E_{sys(a)} = (E_{PV_D_TOTAL(a)}) (365) \quad (20)$$

where

$E_{sys(a)}$ is the actual yearly energy output from the onshore PV modules

$E_{PV_D_TOTAL(a)}$ is the daily energy output from the onshore PV modules

$$E_{sys(a)} = (107872.97\text{Wh}/\text{day}) (365 \text{ day}/\text{year})$$

$$E_{sys(a)} = 39373634.05\text{Wh}/\text{year} = 39373.63405 \text{ kWh}/\text{year}$$

The Specific Energy Yield for the onshore PV ($SPY_{(a)}$) is expressed in kWh per kWp and it can be calculated as follows [43]:

$$SPY_{(a)} = \frac{E_{sys(a)}}{W_{Array_STC}} \quad (21)$$

$$SPY_{(a)} = \frac{39373.63405 \text{ kWh}/\text{year}}{31.250 \text{ kWp}} = 1259.9562896 \text{ kWh per kWp}$$

3.7.2. The Specific Energy Yield for the Offshore PV Array

The actual yearly energy output from the offshore PV modules is given as;

$$E_{sys(w)} = (E_{PV_D_TOTAL(w)}) \quad (365) \quad (22)$$

where

$E_{sys(w)}$ is the actual yearly energy output from the offshore PV modules

$E_{PV_D_TOTAL(w)}$ is the daily energy output from the offshore PV modules

$$E_{sys(w)} = (110019.60 \text{ Wh /day}) (365 \text{ day/year})$$

$$E_{sys(w)} = 40157154 \text{ Wh/year} = 40157.154 \text{ kWh/year}$$

The Specific Energy Yield for the offshore PV ($SPY_{(w)}$) is expressed in kWh per kWp and it can be calculated as follows [43]:

$$SPY_{(w)} = \frac{E_{sys(w)}}{W_{Array_STC}} \quad (23)$$

$$SPY_{(w)} = \frac{40157.154 \text{ kWh/year}}{31.250 \text{ kWp}} = 1285.028928 \text{ kWh per kWp}$$

3.8. The Performance Ratio for the Onshore PV Array

The performance ratio (PR) ratio is a reflection of the system losses and it is used to assess the installation quality. The performance ratio for the onshore PV array can be computed as follows [43]:

$$PR_{(a)} = \frac{E_{sys(a)}}{E_{ideal}} \quad (24)$$

Where

$PR_{(a)}$ is the performance ratio for the onshore PV array

$E_{sys(a)}$ is the actual yearly energy yield from the onshore PV system

E_{ideal} is the ideal energy output of the array.

Now,

$$E_{ideal} = (W_{Array_STC}) \times (H_{TY}) \quad (25)$$

Where

W_{Array_STC} is the total rated power of the array at STC = 31.250 kWp

H_{TY} is the yearly average daily irradiation, ($\text{inkWh}/\text{m}^2 \text{ or } h$) incident on a tilted surface

$$H_{TY} = 365(H_T) \quad (26)$$

H_T is the daily averaged irradiation, ($\text{inkWh}/\text{m}^2 \text{ or } h$) incident on a tilted surface = 4.89 kWh/m²/day or 4.89h

Therefore ,

$$E_{ideal} = (365) \times (H_T) \times (W_{Array_STC}) \quad (27)$$

$$E_{ideal} = (365) \times (4.89) \times (31.250) = 55776.5625 \text{ kWh}$$

Now, $E_{sys(a)} = 39373.63405 \text{ kWh/year}$. Then;

$$PR_{(a)} = \frac{E_{sys(a)}}{E_{ideal}} = \frac{39373.63405}{55776.5625} = 0.7059$$

3.9. The Performance Ratio for the Offshore PV Array

The performance ratio (PR) ratio is a reflection of the system losses and it is used to assess the installation quality. The performance ratio for the offshore PV array can be computed as follows [43]:

$$PR_{(w)} = \frac{E_{sys(w)}}{E_{ideal}} \quad (28)$$

where

$PR_{(a)}$ is the performance ratio for the offshore PV array

$E_{sys(w)}$ is the actual yearly energy yield from the offshore PV system

E_{ideal} is the ideal energy output of the array.

Again,

$$E_{ideal} = (365) \times (4.89) \times (31.250) = 55776.5625 \text{ kWh}$$

Now, $E_{sys(w)} = 40157.154 \text{ kWh/year}$. Then;

$$PR_{(a)} = \frac{E_{sys(w)}}{E_{ideal}} = \frac{40157.154}{55776.5625} = 0.720$$

4. Results and Discussion

The summary of the results obtained from the foregoing computations are presented in Table 3 along with the percentage increase or decrease between each pair of parameters obtained for the offshore and onshore PV array. According to the results, the offshore ambient temperature is about 5.57% less than that of onshore whereas, the offshore wind speed is 74.86% more than that of the onshore. Furthermore, the offshore effective PV cell temperature is 9.96% less than that of the onshore. The cumulative effect of the differences in atmospheric parameters on the PV cell temperature also resulted to 1.99% higher and better offshore de-rating factor over that of the onshore. Similar to the temperature de-rate factor, in all the other performance parameters considered in Table 3, the offshore PV has 1.99% improvement over that of the onshore. In all, it can be stated that in the onshore and offshore PV systems that are considered, where all the system configurations are the same except the atmospheric (ambient temperature and wind speed) parameters, the effective cell temperature and hence the temperature de-rating factor becomes the differentiating factor. Particularly, all the performance parameters considered and compared are proportionally the same as the temperature de-rating factor.

In any case, the study has been based on annual average values of solar radiation and atmospheric parameters. The results for daily and monthly values may well differ from the annual values. However, such daily and monthly analyses are not considered here due to space constraint. However, from the annual results, the offshore system performs better than the onshore PV system with about 1.99% higher daily and yearly energy output.

Table 3: Summary of the onshore and offshore performance parameters.

S/ N	Parameter	Onshore	Offshore	Percentage (%) Increase or Decrease of Offshore Parameter over the Onshore Parameters
1	The annual average ambient temperature (in °C)	25.74	24.305	-5.57
2	The annual average wind speed (in m/s)	2.8	4.896	74.86
3	The effective average daily PV cell temperature (in °C)	45.8061	41.24525	-9.96
4	PV Cell Temperature De-rating Factor	0.9167756	0.935019	1.99
5	De-Rated Output Power Of PV Modules (watts)	176.479	179.991	1.99
6	The Daily Energy Output of the PV Array (Wh/day)	107.873	110.0196	1.99
7	The actual yearly energy output (kWh/year)	39373.634	40157.154	1.99
8	The Specific Energy Yield of PV Array (in kWh per kWp)	1259.956	1285.029	1.99
9	Performance Ratio	0.706	0.72	1.98

5. Conclusion and Recommendation

5.1. Conclusion

Comparative analyses of the energy yield and other performance parameters of onshore and offshore PV system are conducted and the result showed that the offshore PV system has better performance in terms of higher energy output, better temperature de-rating factor due to lower cell temperature. It has also been found that for the onshore and offshore system analysed with the same system configuration except for the differences in atmospheric parameters, namely , ambient air temperature and wind speed, the main performance differentiating factor is the effective cell temperature and its resultant temperature de-rating factor. The lower the effective call temperature, the higher and better the temperature de-rating factor and hence the better the system performance parameters such as yearly energy, specific energy yield and performance ratio. Consequently, the offshore PV with lower effective cell temperature performed better than the onshore PV system.

5.2. Recommendation for Further Studies

The study so far has considered the annual average values of the solar radiation and atmospheric parameters, the daily and monthly variations are also essential and require. The sizing and economic analysis of the offshore PV system are also needed. All these require further studies so as to provide more detailed techno-economic advantages of the offshore PV over the onshore PV system.

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