Hashim and Hassan
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Impact of high temperature on PV productivity in hot desert climates

Samah M. Hashim[1*] and Rayan I. Hassan[2]

Abstract

Hot dry climate regions enjoy high solar irradiation, albeit with high ambient temperatures. These two factors have a contradictory effect on the power generated from PV systems. This work studies the combined effect of high ambient temperature and high irradiation on the net performance of PV systems. The study is based on monitoring a grid-connected 5 kW PV system installed on the rooftop of the Energy Research Center of the University of Khartoum, Sudan. The performance was monitored by meteorological and power measurement equipment from April 2017 to March 2018. The results showed stable power output from the PV system with an average final yield of 4.57 kWh/kWp and a 0.21 standard deviation from this average value. The stability in power output is due to the compensation of the efficiency degradation due to high temperature by high irradiation in summer. This is combined with the relatively low irradiation in winter compensated by the low temperature effect in winter. The annual deviation of the temperature and irradiation is small in Khartoum due to its proximity to the equator. The semi desert climate, offers Khartoum notably few annual cloudy hours. These characteristics were compared with the annual performance of other countries with different climates. The conclusion from this work on hot dry regions is that despite the negative effect of temperature, the annual output power from the system tends to be stable due to the substitution contributed by the regionally high radiation and the relatively cool winter climate.

Keywords PV systems, Temperature effect, Performance parameters, Khartoum, Hot dry regions

1 Introduction

PV solar systems produce green and affordable electricity in hot-dry regions due to the solar power abundance all the year around. However, the high temperature feature is known to have an adverse impact on efficiency due to the negative temperature coefficient of the generated power. This may amount to −0.45% per °C Dubey et al. [1].

The effect of temperature and irradiance on the PV cell efficiency was well studied and empirically correlated in literature. Evans et al. [2] and Siddig et al. [3] respectively, prescribed the following empirical forms

$$\eta = \eta_{\mathrm{r}}[1 - \beta(\mathrm{T_c} - \mathrm{T_r}) + \gamma \ \log \ \phi] \quad (1)$$

$$\eta_{\mathrm{r}} = [1 + 1.2(1 - \tau)\gamma^{\alpha}] \quad (2)$$

Where η in Eq. 1 is the module efficiency, η_r the reference module efficiency provided by the photovoltaic manufacturer, T_r the reference PV cell temperature (25 °C), ϕ the reference solar irradiance on the module (1000 W /m2), γ the solar irradiance coefficient for the PV module (cell's material dependent), β the temperature coefficient for the PV module (cell's material dependent), T_c the PV cell temperature which depends on the environmental conditions. The authors in [2] suggested a β value of 0.0048 and a γ value of 0.12 for silicon. For Eq. 2, η_r is the normalized cell efficiency, τ is the normalized temperature ($\tau = T_c/T_r$) coefficient γ is the normalized irradiation coefficient and α is a constant that depends

*Correspondence:
Samah M. Hashim
samah@uofk.edu
[1] Department of Electrical & Electronics Engineering, University of Khartoum, Khartoum, Sudan
[2] Sudanese Electric Distribution Company, Khartoum, Sudan

on the solar cell material. It is noticeable from the two equations that the efficiency of the cell increases with the increase of solar radiation and drops with the increase of temperature. Literature on the issue of the impact of high temperature on PV system generation is showing numerous reported contributions. Dubey et al. [1] reviewed the progress in this field. One notable point is their assertion that the PV performance ratio decreases with decreasing latitude because of the temperature effect. Kawajiri et al. [4] went further and linked the performance ratio to the PV potential. This was refuted by Marion et al. [5] stating that "the performance ratio does not represent the amount of energy produced because a system with a low PR in a high solar resource location might produce more energy than a system with a high PR in a low solar resource location". The idea that the performance ratio degrades with latitude was also refuted by Malvoni et al. [6] as they concluded that some PV plants in different climate conditions reported higher performance at lower latitudes.

A number of published studies on the solar resource and use in Sudan was accessed. Mustafa [7] analyzed the solar radiation in Sudan sourced from the Met Office in Khartoum. The author used mathematical models to refine the data. Zein [8] conducted a study on the solar energy potential in Sudan. It included a description of how can Sudan benefit from its high solar resource. Zeinab et al. [9] published a PV-powered architectural residence design for Khartoum using a PVsyst® program; but no physical implementation was conducted. An economic evaluation of a grid-tied PV system for a Khartoum residence was conducted by Ismail & Hashim [10]. They made use of the existing data from the 5-kW system of the Energy Research Center of the University of Khartoum (ERC). The effect of dust on PV performance was offset by regular cleaning of the panels.

This present work concentrates on the net effect of the high radiation and high temperature on performance and productivity throughout the year. A case-study of a system output in a hot dry climate was compared to the parallel performance of documented systems in cooler climates. Regarding the hot climate case, the authors used records of environmental data of Khartoum, Sudan's capital. Its geographic location is: 15° N 32° E (see Fig. 1). The proximity of Khartoum to the Sahara Desert explains its mostly hot and dry climate. Its Köppen-Geiger climate classification is BWh (Arid desert hot) Peel et al. [11]. Ambient temperature and solar radiation do not differ much between summer and winter, nor does the length of the day. There are just few days a year when Khartoum is cloudy. According to Mustafa [7], these climatic conditions make Khartoum suitable for using both thermal and photovoltaic solar energy.

Fig. 1 Khartoum location

The local data for this work was obtained from a 5 kW_p grid-connected PV system located on the rooftop of the ERC. The unit was the first of its kind in Sudan. The objective is to study the performance of the system from a physical ground installation and a simultaneous logging of the meteorological data and output power. The latter included the irradiance and temperature. That helped providing researchers, solar systems companies and energy-related decision-makers in Sudan accurate ground data that helped in sizing of PV systems. The unit was installed in April 2017 and it is working properly ever since. The power produced supports the ERC and feeds the excess power into the Faculty of Engineering Administration building, which happens to be located downstairs.

The paper is structured as follows: Section 2 describes the PV system and the weather station components, Section 3 defines the performance parameters, Section 4 presents the results Khartoum system performance compared with other countries and regions and Section V summarizes the findings of the study.

2 System description

The system used to monitor the PV performance consists of two parts. The PV grid-connected system and the weather station.

2.1 PV grid-connected system

Figure 2 illustrates the PV grid-connected system referred to in this study. It includes the following components:

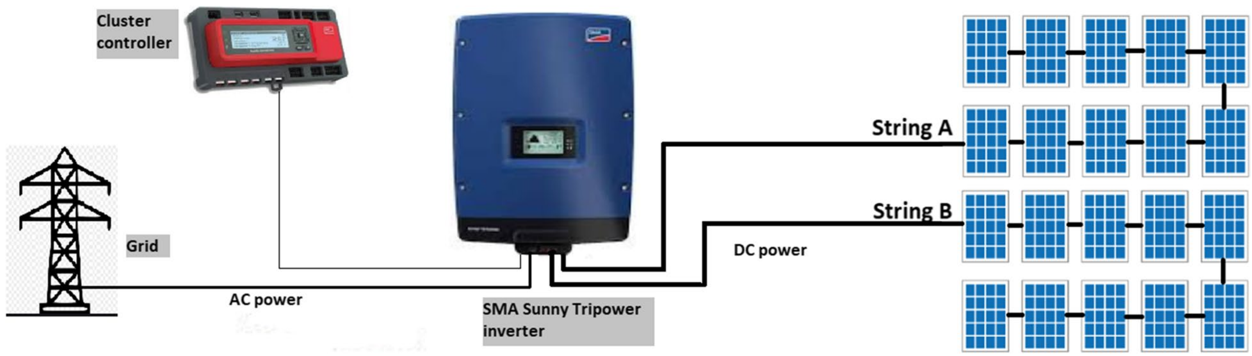

Fig. 2 Layout of the ERC 5-kWp grid-connected PV system

Table 1 Solar modules specifications

PV module	Specification
Type	Monocrystalline Copex®
Nominal maximum power	250 W
Optimum Operating Voltage	30.7 V
Optimum Operating Current (Imp)	8.14 A
Open Circuit Voltage (Voc)	37.4 V
Short Circuit Current (Isc)	8.96 A
Operating Temperature	−40 °C ~ +85 °C
Maximum System Voltage	1000 V (IEC)/600 V (UL)
Maximum Series Fuse Rating	10 A

Fig. 3 PV array at the top of the ERC

– 5 kWp rooftop-installed solar array comprising 20×250 Wp COPEX® Solar modules split into two strings. Its specifications are listed in Table 1. Figure 3 shows a photo of the PV array mounted on the top of the ERC.
– SMA inverter (SMA® SUNNY TRIPOWER 5000TL inverter) converts the direct current of the PV array to grid-compliant three-phase power and feeds it into the grid. Its specifications are listed in Table 2.
– The cluster controller which is a data-logger for the DC input to the SMA inverter and the AC output to the grid.

Table 2 Inverter specifications

Inverter (SMA SUNNY TRIPOWER 5000TL)	Specifications
Input (DC)	
Max. DC power (@ cos φ = 1)	5100 W
Max. input voltage	1000 V
MPP voltage range / rated input voltage	245 V … 800 V/580 V
Min. input voltage / start input voltage	150 V / 188 V
Max. input current input A / input B	11 A / 10 A
Output (AC)	
Max. AC apparent power	5000 VA
Rated power (@ 230 V, 50 Hz)	5000 W
AC grid frequency / range	50 Hz, 60 Hz / -5 Hz + 5 Hz
Rated power frequency / rated grid voltage	50 Hz / 230 V
Max. output current	7.3 A
Power factor at rated power	1
Max. efficiency	98%

The output power from the system is recorded every 5 minutes and aggregated in hourly intervals to be used in the performance analysis of Section 2.3.

2.2 The weather station

The second part of the system is the wind and solar measurement and logging station from Ammonit®, shown in Fig. 4. It uses a horizontally installed pyranometer with a solar reference cell to measure the global horizontal irradiation (GHI). It includes also temperature and humidity sensors.

Fig. 4 Wind and solar measurement station- ERC rooftop

The wind and solar data from the measurement device are recorded every 10 minutes since 2017-03-19. This study used only the irradiance and the ambient temperature data. For this purpose, the data frequency was converted to one reading per hour.

2.3 Definitions of the performance parameters

To measure the performance of the installed PV system the IEC 6724 standard definition of the performance parameters was used Marion et al. [5]. The quoted standard definitions are as follows:

2.3.1 The final yield Yf

The final yield is the AC energy output per kW of the installed PV system divided by the rated output power from the PV array at STC. The energy can be calculated for any period and the yield will be for this period. The yields are: The daily yield, the monthly yield, and the yearly yield. For this study, the monthly yield was used.

The AC output power was read from the SMA inverter data using the attached cluster device described in Section 2.1. The rated output power for this system was 5 kW_p.

The daily final yield is found by dividing the output AC power of the system by the rated DC power from the PV array

$$Y_{f,d} = \frac{E_{AC,d}}{P_0} \tag{3}$$

where:

$E_{AC,d}$ accumulated AC output power from the PV system per day on an hourly basis [kWh].

P_0 rated output power [kW].

The monthly average final yield is

$$Y_{f,m} = \frac{1}{N}\sum_1^N Y_{f,d} \tag{4}$$

Where N is the number of days per month.

The final yield normalizes the system output. This gives the observer an indication of the losses of the system due to both system losses and weather conditions, for any system size.

2.3.2 The reference yield Yr

The reference yield is defined as the irradiation at a specific location for a period (daily, monthly, or yearly accumulated irradiation) divided by 1000 W/m^2, i.e. the irradiation at STC.

The hourly irradiance was measured by the Weather Station described in Section 2.2. The daily reference yield is

$$Y_{r,d} = \frac{G_d}{G_{STC}} \tag{5}$$

where.

G_d accumulated irradiance per day in hourly basis [kWh/m^2]

G_{STC} irradiance at STC, i.e. 1000 [W/m^2]

The monthly average reference yield is

$$Y_{r,m} = \frac{1}{N}\sum_1^N Y_{r,d} \tag{6}$$

Where N is the number of days per month.

The reference yield indicates the actual solar input to the system for a given period normalized to the standard conditions which can be defined also as the number of hours of maximum irradiation. This last definition is used to compare different locations for their input solar irradiation.

2.3.3 Performance ratio PR

The performance ratio is defined as the PV system output divided by the solar irradiance input. This represents the PV system efficiency.

The monthly performance ratio is

$$PR_m = Y_{f,m}/Y_{r,m} \tag{7}$$

The performance ratio indicates the overall effect of losses on the array's rated output due to array temperature, incomplete utilization of the irradiation and system component inefficiencies or failures.

An annual average of the monthly performance ratios can be used to compare different PV systems in different locations to find the losses due to both the system components and the weather conditions.

2.3.4 Seasonal index

In addition to the standard performance parameters anther parameter is added to reflect the stability of the output power system against seasonal variations which is introduced by World bank [12] and described by Eq. (8) below

$$Seasonal\ index = Max\ [m_1, m_2, \ldots, m_{12}]/Min\ [m_1, m_2, \ldots, m_{12}] \tag{8}$$

Where m_i is the output power in month i. Small seasonal index indicates high output power stability against seasonal variations.

All the above parameters were calculated for this work and compared with the same parameters in different countries and regions in the next section.

Table 3 Summary of the PV system performance in Khartoum

Month	$Y_{f,m}$ [kWh/kW_p]	$Y_{r,m}$ [kWh/G_{stc}]	P_r	Wind speed m/s	Ambient temp [°C]
17-Apr	4.52	6.35	0.7	4.44	33.9
17-May	4.61	6.75	0.7	3.73	34.6
17-Jun	4.57	6.59	0.7	3.59	35.1
17-Jul	4.58	6.46	0.7	4.37	32.9
17-Aug	4.27	5.04	0.9	2.00	30.6
17-Sep	4.71	5.61	0.8	1.77	33.3
17-Oct	4.87	5.66	0.9	1.75	33.3
17-Nov	4.68	5.45	0.9	1.95	28.8
17-Dec	4.09	5.14	0.8	1.71	27.4
18-Jan	4.88	5.44	0.9	2.23	22.5
18-Feb	4.57	5.6	0.8	1.73	29.4
18-Mar	4.52	6.01	0.8	1.68	31.3

3 Results and discussion

The total power produced from the 5 kWp PV grid-connected system in Khartoum from April 2017 to March 2018 was 8343 kWh. Table 3 shows the monthly average performance parameters for this system along with the average ambient temperature and average wind speed.

The average final yield, reference yield, performance ratio, and ambient temperature are 4.57kWh/kW_p, 5.84kWh/G_{STC}, 0.79, and 31.1 °C, respectively.

The 0.79 performance ratio is above the performance ratio range of 0.65–0.70 stated by Kawajiri et al. [4] for this region.

Another observation is the small variance in the irradiance within the year, as can be seen in Fig. 5. This

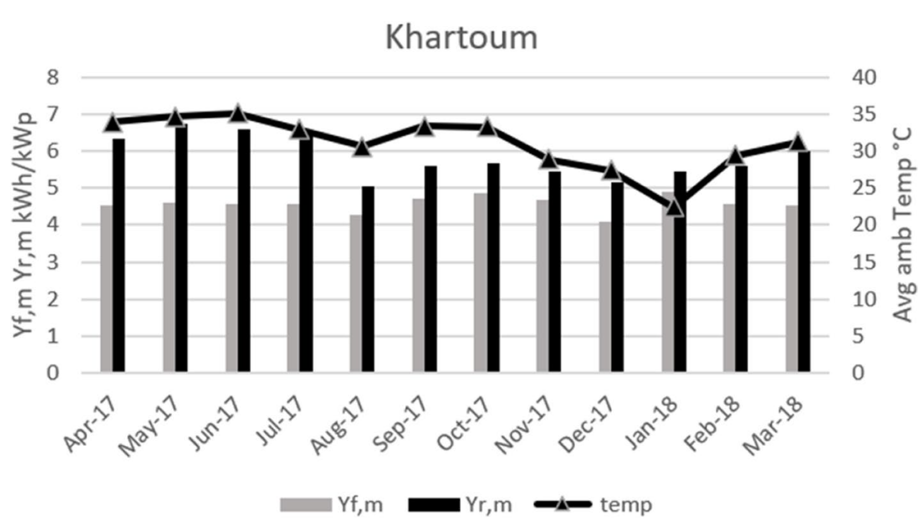

Fig. 5 Performance of the PV system for 1 year in Khartoum

observation was stated by Goetzberger & Hoffmann [13] when comparing the irradiation in Khartoum and Freiburg, southern Germany.

Figure 5 shows an almost constant output power indicated by ($Y_{f,m}$) through the year, with 0.21 standard deviation from its mean value and low seasonal index of 1.2. This eliminates the need for seasonal storage of energy, daily energy storage should be sufficient for reliable power generation from PV power stations in Khartoum. Khartoum has the high average ambient temperature of 31.1 °C.

Figure 6 shows the inverse relation between the ambient temperature and the performance factor for the studied PV system. Still, the minimum output power was in December which indicates that the effect of low irradiance in winter has more effect than the loss due to high temperature in summer.

Table 4 summarizes the performance parameters for the PV grid-connected systems in different countries. The data on this table is compiled from the mentioned references. The countries in Table 4 are in ascending

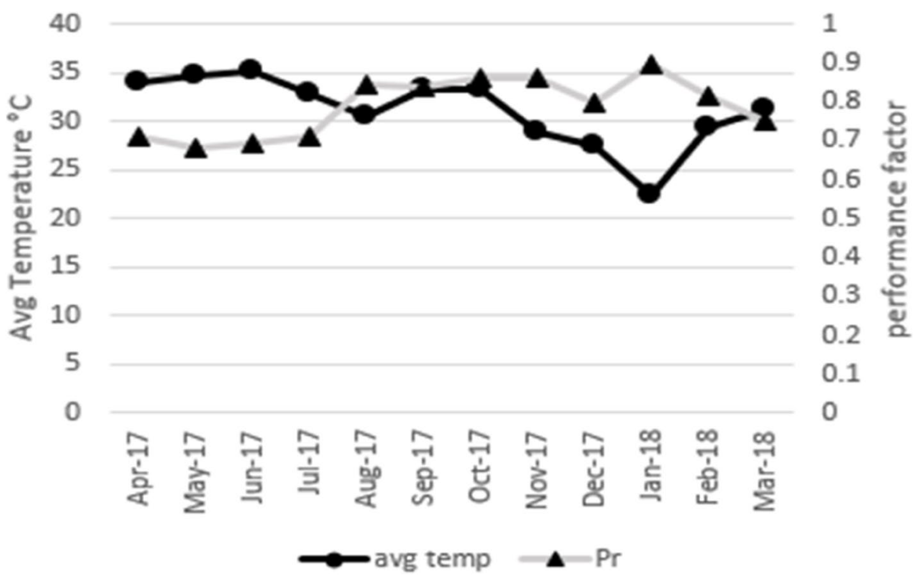

Fig. 6 Performance ratio vs average temperature, Khartoum

Table 4 Summary of PV system performance for different countries ordered by their average ambient temperature

City, country	Dublin, Ireland	Niš, Serbia	Kerman, Iran	Adrar, Algeria
System size [kWp]	1.72	2.00	11.04	2.5
$Y_{f,m}$ [kWh/kWp]	2.4	2.82	4.81	4.81
$Y_{f,m}$**std**	0.84	1.42	0.4	0.49
$Y_{r,m}$ [kWh/kW]	2.85	3.79	5.69	6.35
PR	0.87	0.74	0.86	0.76
Seasonal index	3.1	8.4	1.3	1.4
Ambient temp [°C]	13.1	13.9	21.7	28.1
Source	[14]	[15]	[16]	[17]
City, country	Muscat Oman	Khartoum, Sudan	Djibouti, Djibouti	Sawda, Kuwait
System size [kWp]	1.4	5.0	302.4	21.6
$Y_{f,m}$ [kWh/kWp]	4	4.57	4.59	4.77
$Y_{f,m}$**std**	0.46	0.21	0.42	0.71
$Y_{r,m}$ [kWh/kW]	6.29	5.84	5.62	5.96
PR	0.64	0.79	0.82	0.80
Seasonal index	1.5	1.2	1.3	1.6
Ambient temp [°C]	29.6	31.1	33	34
Source	[18]	Current work	[19]	[20]

ambient temperature order. It can be seen that the final yield standard deviation is generally small for high ambient temperature countries and Khartoum has the smallest final yield standard deviation, which indicates high stability of the power generated all through the year. This is because of the linear relationship between the ambient temperature and the irradiation and, subsequently, the power generation as reported by previous publications such as Dubey et al. [1].

From Table 4 it can be noticed that seasonal index reflects the stable output power against seasonal variations from the systems in hot dry regions. Khartoum showed the smallest seasonal index 1.2. and a high seasonal index for Serbia of 8.4.

In Fig. 7, the average performance ratio for the studied countries is plotted along with the ambient temperature.

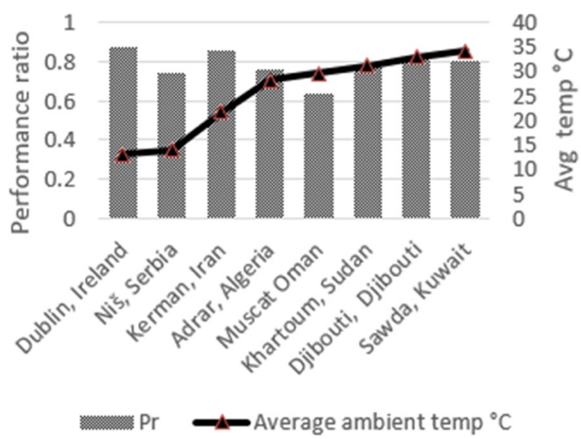

Fig. 7 Performance ratio and ambient temperature for different countries

The figure shows that there is no clear relationship between these two parameters. This result indicates that the previous work of Kawajiri et al. [4], which depended on NASA surface meteorology, should be revised and compared with data from weather ground stations such as those of [14–20].

Figures 8 and 9 show the variations in the output power indicated by the final yield, the input power indicated by the reference yield, and the ambient temperature in Ireland and Djibouti. Ireland (Fig. 8), a cold weather sample, has a final yield in February of 1.20 kWh/kWp and 4.6 kWh/kWp in August. This difference shows that for PV grid-connected systems the generation from the PV system has high variation through the year which needs seasonal arrangements of grid generators. On the other hand, a hot weather country, such as Djibouti (Fig. 9) which is in the same latitude as Khartoum (15° N) shows relatively constant power generation all around the year. These results are close to those obtained in this current work for Khartoum.

4 Conclusion

This work is the first to monitor the performance of a grid-connected PV system in Khartoum. The system had an average final yield of 4.57 kWh/kWp which is high among similar systems in other locations despite the high ambient temperature in Khartoum. The final yield was effectively stable in the whole year of observation with a 0.21 standard deviation. The reasons for this stability of the output power generated by the system are (i) the limited monthly variation in irradiance in Khartoum, (ii) the combination of high irradiance and high temperature in the summer

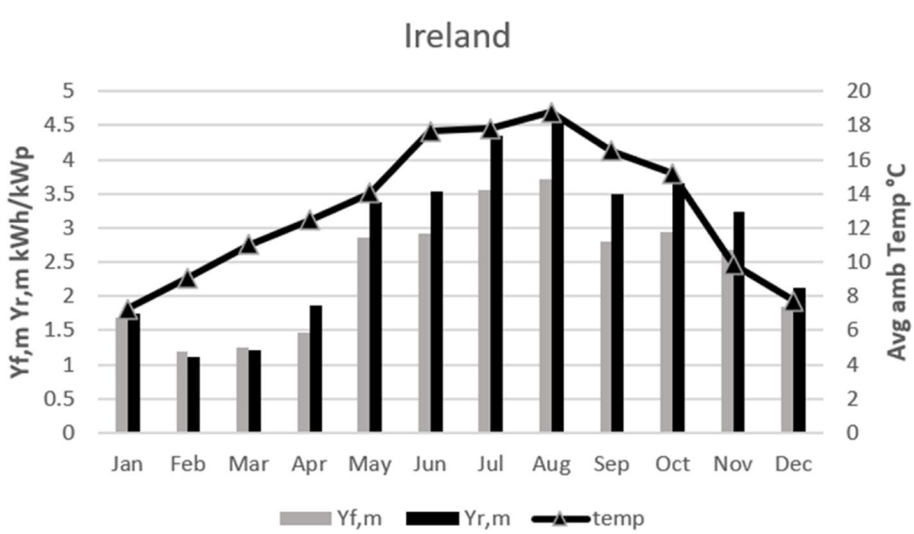

Fig. 8 Performance parameters for Ireland compiled from Ayompe et al. [14]

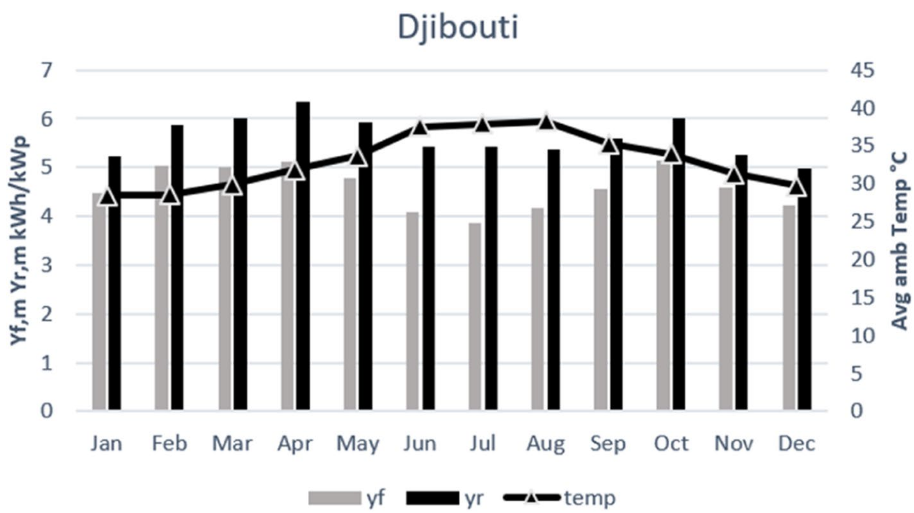

Fig. 9 Performance parameters for Djibouti compiled from Daher et al. [19]

season and the relatively low-temperature and relatively low-irradiance in winter. Their inverse effects are seen to balance each other. This sort of match is related to the proximity Khartoum's latitude to the equator.

The results of this work are seen to indicate that the negative effect of high temperature in solar power generation and the performance ratio values of PV systems should be reconsidered as from surveying much previous work in different countries the results from ground data stations are different from the results from satellite data.

The results of this work reflect the validity of the hypothesis presented that for hot dry regions the conflicting summer conditions of high irradiance and high ambient temperature results in a stabler annual power output which was evident in the values of the low seasonal index of hot dry regions compared to cold regions. This works out to minimize the need for hybridization and storage. Projection of these results to environmentally similar regions can enhance feasibility and relax the hot-climate stigma currently tied to these regions.

5 Nomenclature

AC Alternating Current

DC Direct Current

E_{AC} AC output Energy

ERC Energy Research Center of the University of Khartoum

G irradiance W/m^2

GHI Global Horizontal Irradiation

P peak output power

P_0 rated output Power

PR Performance Ratio

PV Photovoltaic

STC Standard Test Condition, 25oC temperature, $1000W/m^2$ irradiance and 1.5AM

Std Standard deviation

Y_f final Yield

$Y_{f,d}$ daily final Yield

$Y_{f,m}$ monthly final Yield

$Y_{r,m}$ monthly reference Yield

Y_r reference Yield

$Y_{r,d}$ daily reference Yield

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Authors' contributions

Dr. Samah M. Hashim is the first author, she is responsible of all the research work analysis and research writing. Eng. Rayan contributed in the data manipulation and conversion. The authors read and approved the final manuscript.

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Availability of data and materials

The meteorological data is available at the server in the energy research center in the University of Khartoum.

Declarations

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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