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RESEARCH

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Assessment and performance analysis of roof-mounted crystalline stand-alone photovoltaic (SAPV) system at selected sites in South Africa

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Abstract

Background: Technology is deployed to take the advantage of the ultimate energy from the sun (solar energy) to be used as heat or clean electricity. This energy is classified as "sustainable energy" or "renewable energy" because it requires a short period to naturally replenish the used energy. The application of solar energy involves the conversion of the natural energy resource into a usable form, either as heat or as electricity. The device consists of solar cells made from semiconductor materials, such as silicon, cadmium telluride, gallium arsenide, and so on. Solar potential is both location- and climate-dependent; it is characterised by low energy intensity and intermittency, which limit its application; an improvement in photovoltaic (PV) system performance will facilitate more deployment of the clean electricity system. Therefore, this study provides PV potential and system information required for reliable and optimised solar PV systems at chosen locations. This work uses a 5-stage solar PV system assessment and system performance evaluation utilising Solargis Prospect software. The PV potential and system performance of nine selected site locations in South Africa was conducted using this method. The nine PV site locations are Bloemfontein (Free State), Germiston (Gauteng), Mahikeng (North-West), Mbombela (Mpumalanga), Musgrave (Kwazulu-Natal), Musina (Limpopo), Port Nolloth (Northern Cape), Port Elizabeth (Eastern Cape), and Worcester (Western Cape).

Result: The results of the study were categorised into PV meteorological and system performance parameters as follows. Photovoltaic meteorological parameters—the site in Mahikeng has the highest global horizontal irradiance (GHI), 2156 kWh/m^2, and a corresponding specific PV power output (1819.3 kWh/kWp), closely followed by Bloemfontein (2111.5 kWh/m^2, 1819.4 kWh/kWp) and Port Nolloth (2003.2 kWh/m^2, 1820.5 kWh/kWp). The lowest GHI (1645.1 kWh/m^2) and specific PV power output (1436.6 kWh/kWp) were recorded in Musgrave. Photovoltaic system performance parameters—the range of performance ratio (PR) between 75.8 and 77.7% was reported across the nine sites. This ratio met the acceptable benchmark of PR. The highest specific PV power output loss, 118.8 kWh/kWp, was obtained at sites in Bloemfontein, Mahikeng, and Port Nolloth, while the lowest, 93.8 kWh/kWp, was in Musgrave.

Conclusions: The results of the solar PV potential assessment and the evaluation of PV systems performance in the chosen sites across the nine provinces of South Africa show huge PV potential and energy yield. From the results, it was observed that the range of the yearly average of: (1) GHI among the sites is 1645.1–2156 kWh/m^2; (2) direct normal irradiation among the sites is 1785.3–2559.3 kWh/m^2; (3) diffuse horizontal irradiation among the sites is 512.5–686kWh/m^2; (4) global tilted irradiation among the sites is 1849.2–2397.1 kWh/m^2; (5) the temperature (TEMP) among

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the sites is 16–23 °C; (6) specific PV power output (PVOUT specific) among the sites is 1436.6–1820.5 kWh/kWp; (7) total PV power output (PVOUT total) among the sites is 14.366–2397.1 MWh; and (8) the performance ratio among the sites is 75.8–77.7%. Based on the solar resource and performance results of the PV system obtained, the deployment of monocrystalline solar PV technology in all the considered sites across South Africa is technically viable.

Keywords: Solar energy, Energy conversion, Solar photovoltaic, Solar PV system, Stand-alone PV system, Solar radiation, Solargis Prospect, PV performance

Background

The global energy demand is on the increase due to population, industrialisation, and urbanisation growth. Globally, urbanisation is expected to extend to all the regions by 2050 and the growth will be faster in Asia and Africa than in other regions. An urbanisation rise of 56% and 64% has been projected for Africa and Asia, respectively (UN 2014). For several years, fossil fuels, such as petrol, coal, diesel, and natural gas, have provided the needed energy to meet the identified growths, and in 2018, about 64.2% of the global electricity was generated from fossil fuels (BP 2019). The energy sources for generating electricity are shown in Fig. 1. Today's large economies, such as the USA and Germany, were built and driven by fossil fuels, and this makes fossil fuels efficient economic development drivers (Ebhota 2019a; Ebhota and Tabakov 2020). However, this comes with negative health and environmental consequences. Studies have linked climate change, global warming, and greenhouse gas (GHG) emissions to the burning of fossil fuels for electricity generation (Baz et al. 2021; Srivastava et al. 2021; Vohra et al. 2021). Among the components of GHG, carbon dioxide (CO_2) contributes the most to global warming, thereby becoming one of the critical challenges confronting humanity. Simultaneously, there is continuous depletion of fossil fuel reserves, increase and fluctuation of prices, subsidy challenges, and increasing awareness of ecological, green, or sustainable consumerism. Despite these deleterious consequences, man is not deterred from fossil fuel usage, as fossil-based energy is still heavily being consumed year in and year out. Growth rates of 1.5% and 2.9% were reported for 2007–2017 and 2018, respectively (BP 2019). The global annual fossil fuel consumption and gas growth rates were reported to rise by 1.6% and 1.5%, respectively; the rise is mostly from developing regions, such as sub-Saharan Africa and Asia (BP 2019;

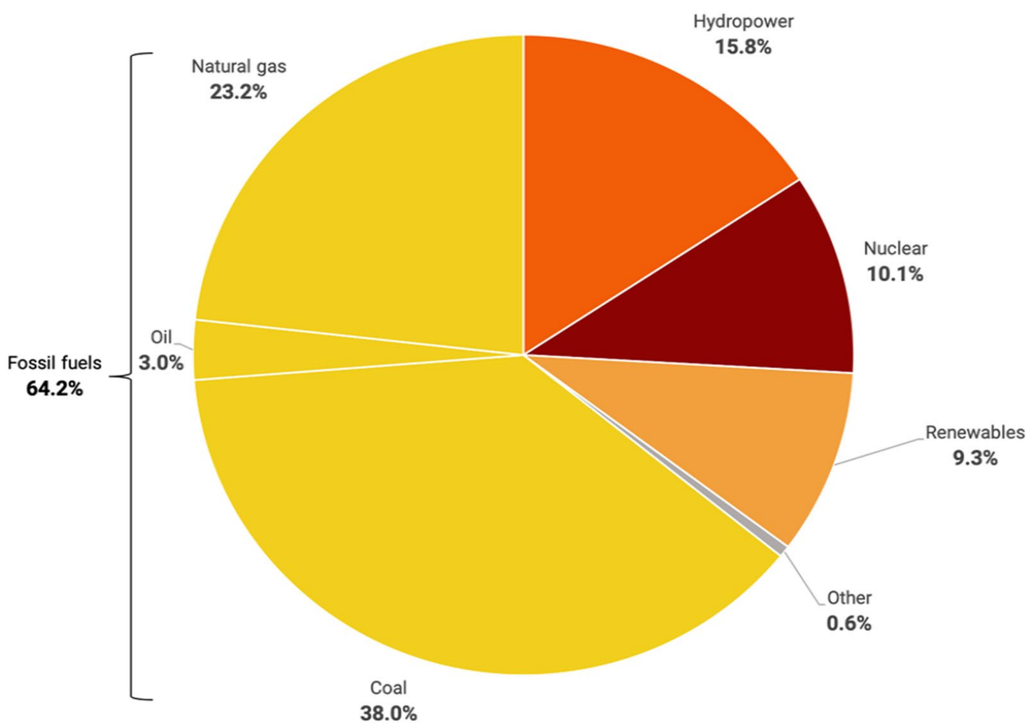

Fig. 1 Sources of global electricity generation (BP 2019)

WorldBank 2021). This is due to energy poverty in developing countries, especially in rural areas, where biomass (charcoal and firewood) is the main source of energy for cooking (Ebhota 2019b).

To address the challenges emanating from the use of fossil fuels, the United Nations (UN), under the sustainable development goals (SDGs), came up with a universal clarion call that targets the reduction in CO2 emissions (UN, 2015, 2020; Ebhota 2021). One of the goals of SDGs is the provision of clean, adequate, and affordable energy for all by 2030. The human existence will be threatened if there is no energy to support socio-economic activities. It implies that the reduction or elimination of fossil fuels is only possible if there are alternative energy supplies. Several renewable energy sources, such as solar, geothermal, tidal, biofuels, nuclear, hydro, and wind, have been identified and are being exploited as alternatives to fossil fuels. The deployment of renewable energy technologies has been challenging because of their intermittency in supply, low energy densities, and uneven spread of resources. Solar energy is the commonest renewable energy and its potential is region dependent. As a result, research and development activities have been focussed on solar efficiency, optimisation, energy storage, and cost. Prices of solar photovoltaic (PV) parts, especially PV modules, have witnessed a drastic decline of over 50% in recent years (U. S. 2015); however, the conversion efficiency of most commercially available crystalline silicon PV panels is from 15 to 20%, while concentrated multifunction and other new cells are between 40 and 50% (Kammen and Sunter , 2017, 2016, 2020; NREL).

The exploitation of solar PV energy is limited by several factors, which include location, low energy densities, and low conversion efficiency. Site location conditions, such as season, length of sunshine, time of the day and year, speed of the wind, topography, relative humidity (RH), temperature, and many other environmental factors determine solar PV potential and performance. The estimation and understanding of these factors play an invaluable role in the accurate assessment of solar PV potential and performance prediction of a solar PV system. This implies that inaccurate assumptions of solar resources and sizing of PV systems often lead to either system's under-sizing or over-sizing, erratic power supply, and higher cost.

The previously published solar PV-related studies of the regions under consideration were mainly focussed on the econo-technical feasibility assessment (Semelane et al. 2021; Stanley et al. 2021; Mutombo and Numbi 2019; Zawilska and Brooks 2011) and the significance (Conway et al. 2019; Kumar et al. 2019; Meyer and Overen 2021) of the solar PV system. Studies on the assessment of solar PV potential and systems performance across the nine provinces of South Africa could not be found. Again, a comparative analysis of solar PV potential and systems performance across the nine provinces of South Africa could not also be found. Therefore, this study aims to assess the solar PV potential and predict the performance of PV systems in selected locations across the nine provinces of South Africa. Computer modelling of a hypothetical PV system of a 10 kWp installed capacity of tilted rooftop monocrystalline PV modules will be used in this assessment and performance prediction study. This study with the aid of computer modelling will proffer answers to the following research questions—what is the range of the yearly average:

1. Global horizontal irradiation (GHI) among the sites?
2. Direct normal irradiation (DNI) among the sites?
3. Diffuse horizontal irradiation (DIF) among the sites?
4. Global tilted irradiation (GTI) among the sites?
5. Temperature (TEMP) among the sites?
6. Specific PV power output (PVOUT specific) among the sites?
7. Total PV power output (PVOUT total) among the sites?
8. Performance ratio (PR) among the sites?

To address the set objectives satisfactorily, the paper was expressed in four sections ("Background, Methods, Results, and Discussion"), in addition to the background in "Background" section. "Methods" section presents the methods, "Results" section presents the simulation results, and "Discussion" section discusses the results as they connect to the existing literature. Finally, critical points and responses to the research questions are highlighted in "Conclusions" section, the concluding section.

Solar radiation and PV system

Solar radiation is the emission of energy from the sun, which travels through space as either waves or particles, and can take the form of heat, light, or sound. These waves or particles can be categorised into four types: alpha, beta, neutrons, and electromagnetic waves. This study focuses on electromagnetic radiation. Electromagnetic solar radiation has been described as a phenomenon by which the sun emits energy in the form of a wave at the speed of light. This electromagnetic radiation emitted by the sun is often called solar radiation or just sunlight. Incidentally, solar radiation is the most abundant renewable energy resource in nature that can alternatively replace fossil fuels. The sun releases radiation at a rate of 3.72×10^{20} MW, and the earth's surface receives only about 40% of this energy (Lumen 2021; Iqbal 1983). The energy received from the sun is called incoming solar radiation or insolation. A variety of technologies have been developed and deployed to capture and convert solar radiation into vital forms of energy, such as heat and electricity. Solar PV technology is used to convert the received sunlight or radiation into useable electricity. Light photons release energy to the electrons once the PV cells in the solar panels absorb light and this drives the electrons to flow through the material as a current (Wikipedia 2018). The PV system consists mainly of a solar PV panel, charge controller, inverters, battery, and distribution board, as shown in Fig. 2.

The PV system is either off-grid (with battery) or grid-connected system (without battery). The solar PV panel receives the sun's irradiance and produces a direct current (DC) power from it. The DC power generated, which is the product of voltage and current, is linked to the inverter that converts the DC voltages to alternating current (AC) voltages. The meter coupled with the fuse box, helps the grid to receive the AC output and to inject the electricity safely and efficiently into the grid. The meter could be twin meters or a single bidirectional meter, used to record the net amount of electricity taken from or given to the grid. Generally, the grid-connected PV system is made up of solar PV panel arrays, a solar inverter, electrical panel, array mounting racks, cabling, meters, combiner box, surge protection, disconnects (array DC disconnect, inverter DC disconnect, inverter AC disconnect, exterior AC disconnect), and grounding equipment and other electrical accessories. The off-grid or stand-alone solar PV systems are usually not connected to a grid, but to a bank of batteries that store the power generated by the solar modules, and are then linked to the electrical loads.

Classification of solar radiation

Solar radiation is absorbed and/or deflected by the extra-terrestrial bodies along its path or diffused through them. The amount of radiation absorbed per unit of a horizontal area is called insolation, and the extent of absorption depends on the solar zenith angle and distance of the earth from the sun.

Three components of radiation are formed as it gets to the earth's surface, as shown in Fig. 3

- *Direct radiation* The unobstructed direct radiation from the sun that is intercepted by the earth
- *Diffuse radiation* Indirect radiation sent to the earth's surface from all directions. The radiation is dispersed and reflected on the earth's surface by solid bodies, and atmospheric constituents, such as molecules, dust particles, and clouds.
- *Reflected radiation* A radiation reflected off its path as it hits on surface features along its line of travel.

Direct radiation is the largest among these components, followed by diffuse radiation while reflected radiation is the least. However, reflected radiation of locations surrounding highly reflective surfaces, such as snow and glass, may be high. The addition of these three forms of radiation is called total or global solar radiation (Cotfas, 2021; ESRI-ArcGIS 2021).

Methods

This study deploys computational modelling, adopting the normal 5-stage solar PV assessment and system's performance evaluation approach using Solargis

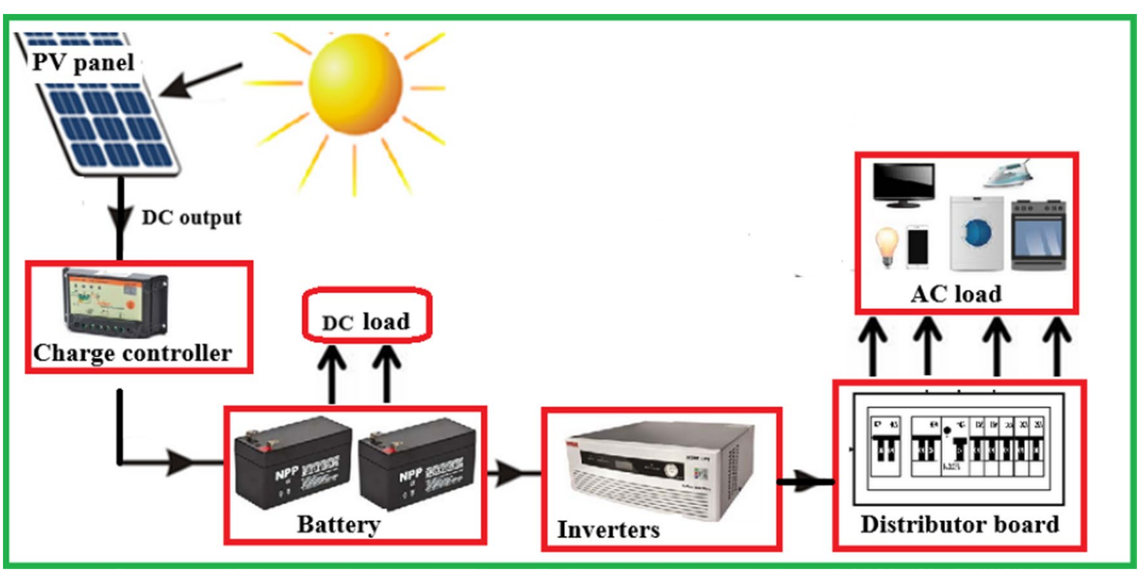

Fig. 2 Main components of a stand-alone solar PV system

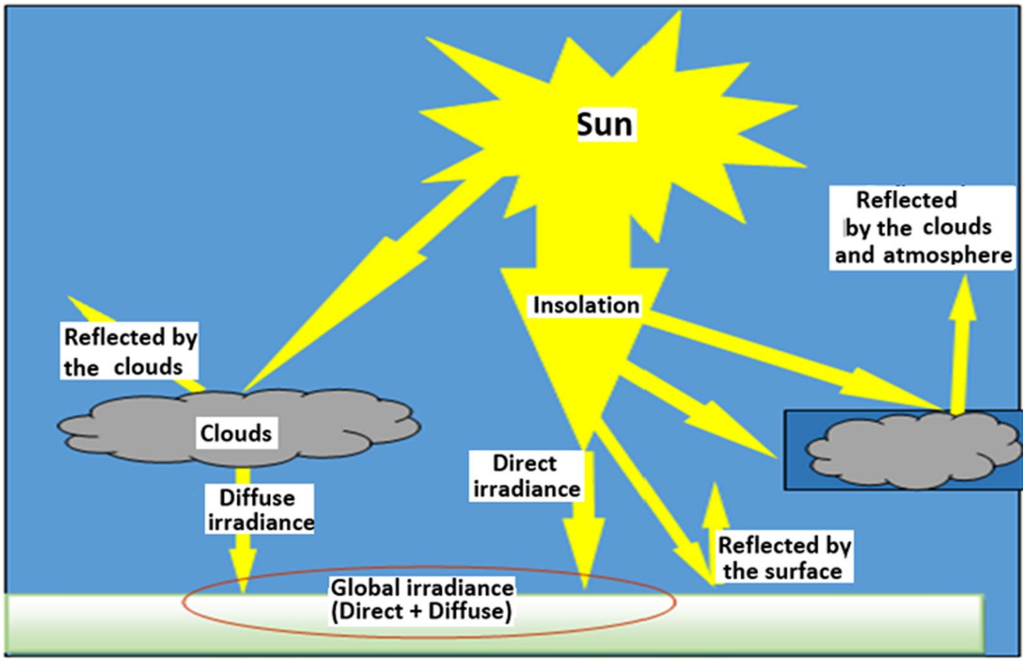

Fig. 3 Components of total/global radiation (direct, diffused, and reflected radiations)

Prospect, a solar PV system design and simulation software application. An iteration between PV module geometry in stage 1 and the second stage will be introduced to allow a switch between the selected locations. The first stage involves the description of the site location using latitude and longitude, coordinate or physical address. In the second stage, the site information will be used to generate meteorological components required for simulation. The third stage will deal with the configuration of a hypothetical 10 kWp stand-alone solar PV system of panel mounting geometry, selection of PV cell, and user's need definition. In the fourth stage, here, the generated information in both stages 2 and 3 will be used for simulation. The fifth stage will be the reporting of simulation results generated in stage 4. Both the meteorological and PV system performance will be extracted from the generated reports. The reports, which will be obtained from Solargis Prospect, will be used to examine the solar resource level, exploitation viability, and the likely challenges. Solargis Prospect was chosen among the solar PV systems computer modelling applications because of its simplicity, friendly user interphase, availability, accuracy, and explicit report. Some of the PV system design and simulation software applications and uses are presented in Table 1.

The block diagram and flow chart of the 5-stage solar PV assessment and system performance evaluation method are depicted in Fig. 4a, b, respectively.

Use of a simulator: Solargis

The Solargis Prospect software application is an online-based simulator for solar PV sites' potential assessment and PV systems' design, optimization, and performance evaluation. It deploys Google Web Toolkit web programming technology to incorporate numerical simulation standards obtained from the current research with new climate databases. The use of Solargis software requires the following procedure: launching into the online Solargis window; entering the site's coordinates or physical address into the search space; going into the simulation page by clicking continue; defining the capacity of the PV system, selecting PV cell, inverter, DC/AC losses, and entering the orientation (Azimuth/tilt angles). Solargis automatically supplies information, such as cable losses, snow and soiling losses, based on the site's location and the PV system configuration. The last stage of the procedure is the generation of a report, which has results of both PV potential assessment (meteorological parameters) and the system's performance evaluation parameters.

The selected sites description and configuration of a stand-alone PV system

This subsection discusses on-site location description and the configuration of solar PV system in two subsections—The site location, solar PV system description, and the electrical load estimation, respectively.

Table 1 Software applications used for solar PV systems performance analysis (Dondariya et al. 2018; Fuzen 2021; Khatib et al. 2012)

Software	Software specifications	Inputs required
PV*SOL	It is used to carry out planning and simulation of the solar PV system, which includes load consumption and CO_2 emissions saved	Location description, meteorological parameters, system and auxiliary components requirements
Solargis Prospect	It is an online simulation tool, satellite map supported for solar PV systems site evaluation, planning, and optimisation. It can also be applied to the comparative study of energy production among the various PV cell technologies	Type of PV cell technologies, site coordinates, AC/DC losses, cable sizing, load demand
TRNSYS	TRNSYS is a flexible graphically based software applied to simulate the behaviour of transitory systems, mainly used for simulations that are focussed on assessing the performance of electrical and thermal energy systems. TRNSYS can also be applied in the modelling of other dynamic systems, such as biological processes and traffic flow	
PVGIS	It is an open-source research instrument for performing the evaluation of PV systems in geographical regions. Is a policy-making support system for the European union	The mounting position, the sum of irradiance, monthly values of ambient conditions,
PVsys	A PV systems design and simulation software and its scope include—An econo-technical feasibility study, system sizing, and data analysis of complete PV systems. The PV systems considered are stand-alone, pumping, grid-connected, and DC grid	Albedo definition, site location description, system sizing conditions and parameters for a specific project

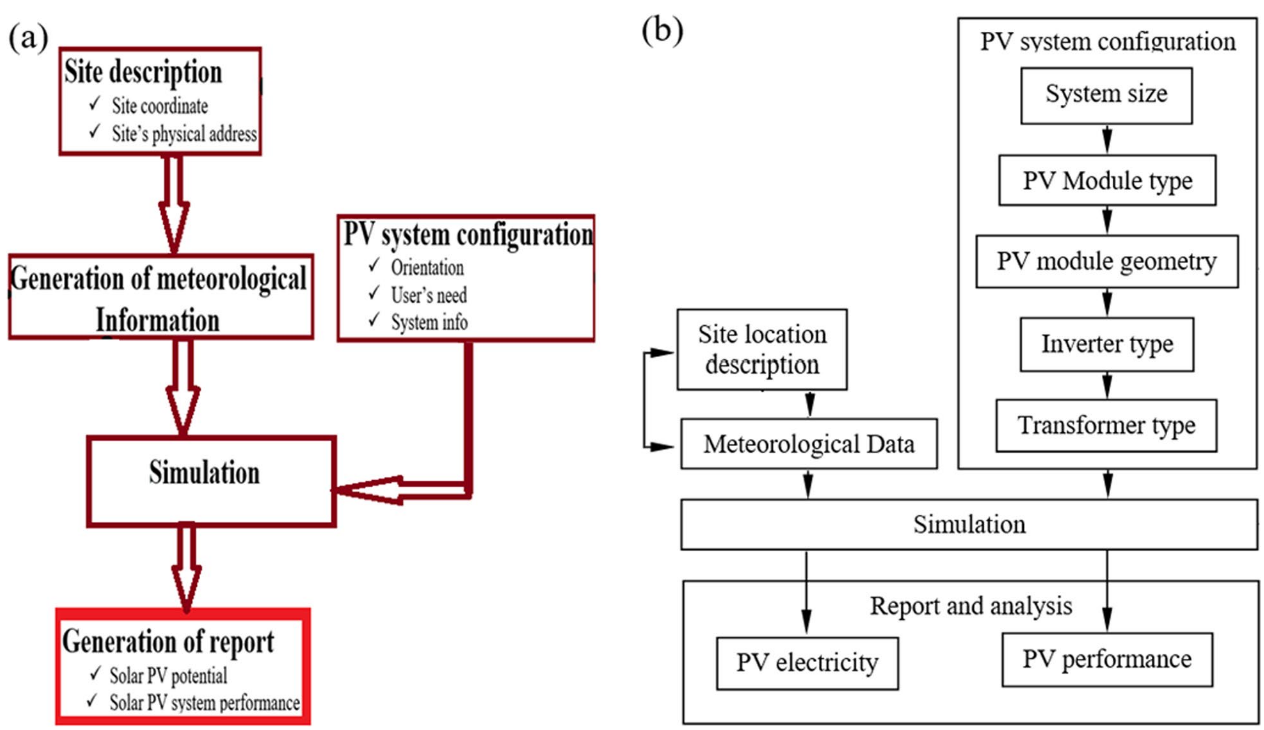

Fig. 4 A 5-stage solar PV assessment and system performance evaluation method; **a** block diagram of the 5-stage and **b** flow chart of the 5-stage method

The site location

The nine provinces for the selected site locations across South Africa are shown in Fig. 5. Site geographical information is required to generate meteorological data that are used to estimate the solar PV potential of a given place. This process is a prerequisite to the evaluation of the performance of a solar PV system, which depends on site-specific meteorological parameters, such as ambient temperature, wind speed, and solar irradiance characteristics.

Other determinant parameters, which include latitude, pollution level, dust, orientation, and tree cover are referred to as site factors. The chosen sites are located in both residential and commercial areas. Table 2 presents the coordinates of the locations of the sites in terms of latitude (° N), and longitude (° E), at different elevations and the same Albedo (0.20).

Solar PV system description

This study uses a hypothetically designed 10 kWp installed capacity of a tilted rooftop mounts solar PV system on a residential building. The solar PV panel's angle of tilt and Azimuth are tilted on the roof such that the panels do not cast a shadow or overlap each other. The PV panels are mounted on rails fixed on a tiled roof, which gives space for backside ventilation. A low-voltage parallel stand-alone connection was adopted to prevent lowering the output of the whole system by an underperforming solar panel.

Table 2 Selected sites and their coordinates

Location	Province	Coordinate (°)	Altitude (m)	Albedo
Bloemfontein	Free State	− 29.12, 26.21	1389	0.20
Germiston	Gauteng	− 26.23, 28.17	1643	0.20
Mahikeng	North-West	− 25.87, 25.64	1278	0.20
Mbombela	Mpumalanga	− 25.47, 30.97	672	0.20
Musgrave	Kwazulu-Natal	− 29.85, 31.00	104	0.20
Musina	Limpopo	− 22.35, 30.04	536	0.20
Port Nolloth	Northern Cape	− 29.25, 16.87	4	0.20
Port Elizabeth	Eastern Cape	− 33.96, 25.61	57	0.20
Worcester	Western Cape	− 33.65, 19.45	232	0.20

The configuration of the PV system and technical information of the system's components used, such as PV panel and orientation, inverter, and battery, are presented in Table 3. The solar PV panel selected is of monocrystalline PV cell with model number CS1-320MS and manufactured by CSI Solar. The panels are mounted on rails attached to a tilted roof of a

Fig. 5 Map of South Africa showing the provinces (Ontheworldmap 2022)

residential building; the azimuth and tilt of the PV panels are optimised and the arrangement allows backside ventilation and prevents panels from shading each other.

Monocrystalline PV cell material was selected because of the quest for higher efficiency and the system is on a fixed stand type that can adequately power a household of a small family. The solar PV stand-alone system is made up of the following components: controller, PV array, inverters, fuse box, and battery. The circuit layout of the stand-alone PV system is shown in Fig. 6.

Results

The results obtained are functions of both location and the PV system information described in "Discussion" section, which serve as inputs for the simulation process. The section is divided into two segments: solar resource assessment: solar PV potentials limiting factors and energy system degradation and losses.

Solar potential assessment: solar radiation parameters and meteorological data

This subsection presents solar potential assessment results in terms of the following solar radiation and meteorological parameters:—Solar insolation parameters GHI, DIF, DNI, Specific PV power output (PVOUT specific) and total PV power output (PVOUT total) of the selected sites; and meteorological data ambient temperature, relative humidity (RH), and speed of wind (SW).

Solar insolation

This report is primarily based totally on the high-decision sun and meteorological database developed and managed through Solargis. The statistics parameters provided in this report, are estimated through Solargis models and algorithms. The data inputted into the models come from different sources and the data properties include monthly and yearly long-term statistics (having 365 days) and covering from January 1, 1994/1999/2007 to December 31, 2018, depending on geographical region. The solar radiation parameters as extracted from the reports obtained from Solargis Prospect are presented in Figs. 7, 8, 9, and 10. The profile of yearly solar radiation, a specific meteorological parameter that determines solar electricity generation, and power of a PV power system are presented in Fig. 7a. The corresponding yearly specific PV power output and PR of the selected sites are shown in Fig. 7b. The result

Table 3 System information

PV field orientation		Models used				User's needs	
General information: stand-alone							
Installation type	Roof mount	Transposition	Perez			Daily consumption (kWh/Day)	2.56
Azimuth/inclination	0° (north)/30°	Diffuse	Perez, meteonorm			Controller	
Horizon		Circumsolar	Separate			Technology	MPPT
Free horizontal	No shading	At operating conditions (50 °C)					
PV module		Pmpp (kWp)	2325	U mpp (V)	64	I mpp (A)	36
Manufacturer	CSI Solar	Unit Nom. Power (Wp)	320			Nominal (STC), kWp	2.560
Model	CS1-320MS	Number of PV modules (units)	8			Modules	4 Strings × 2 In series
PV module type	cSi—monocrystalline silicon	Designed system size (kWp)	10				
Total PV power							
Nominal (STC) (kWp)	3	Total number of modules	8			Module area (m^2)	13.5
Cell area (m^2)	13						
Battery							
Manufacturer		Model					
Technology	Lead acid, seal, gel	Voltage (V)	48			Stored energy (kWh)	47.5
Number of units	6 in parallel × 4 in series	Capacity (Ah)	1200			Temp coeff	− 0.5 m V/℃/Elem
Charging, SOC = 0.90/0.75 (V)	53.7/51.3	Discharging SOC = 0.2/0.45 (V)	47.8/49.7			Threshold command	SOC calc

Here, STC is the standard test conditions; SOC is the state of charge estimating; Pmpp (kWp) is the power at maximum power point; Umpp (V) is the voltage at the maximum power point, and Impp is the actual amperage at MPPT

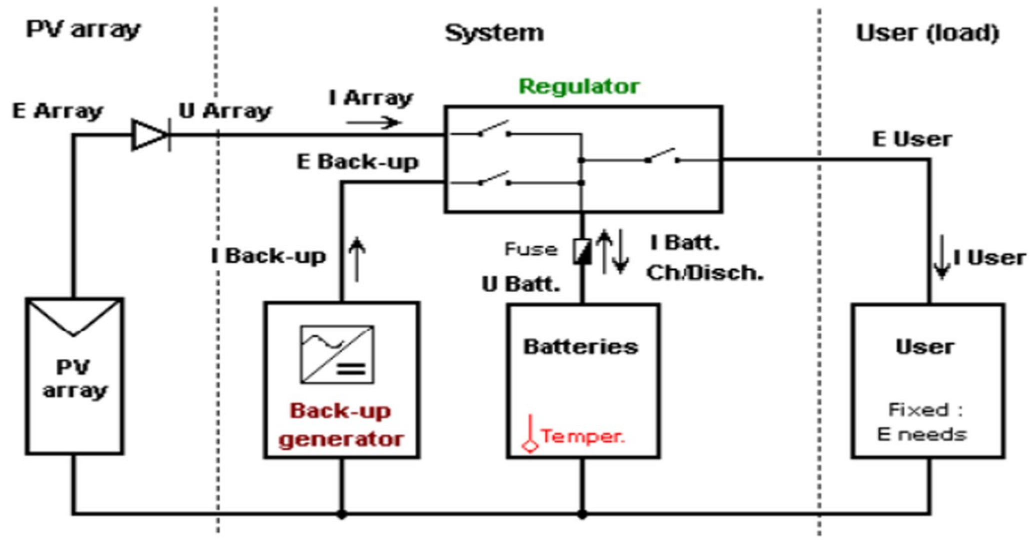

Fig. 6 A layout of the stand-alone PV system

shows that Mahikeng has the highest level of radiation, GHI (2156 kWh/m^2) and a corresponding specific PV power output (1819.3 kWh/kWp), closely followed by Bloemfontein (2111.5 kWh/m^2, 1819.4 kWh/kWp) and Port Nolloth (2003.2 kWh/m^2, 1820.5 kWh/kWp), respectively. This theoretical evaluation of PV electricity generation did not consider PV system components, such as modules, inverters, and battery long-term ageing and performance degradation.

Performance ratio

Performance ratio, which is sometimes referred to as the quality factor, is a parameter to measure the quality of a PV plant and it does not depend on location. It links the actual to theoretical energy outputs of the PV plant and it is expressed in %. In the case of a grid system, PR helps to define the exact net energy proportion (after deduction of own consumption and energy loss) available to be injected into the grid. The correlation between the actual and maximum possible theoretical solar PV system performance is called PR. It is a deviation from the standard PV system performance in real-time situations. It evaluates the performance of a solar PV system, taking into account meteorological factors, such as climate changes, temperature, relative humidity (RH), and irradiation. Additionally, PR considers and reflects panel

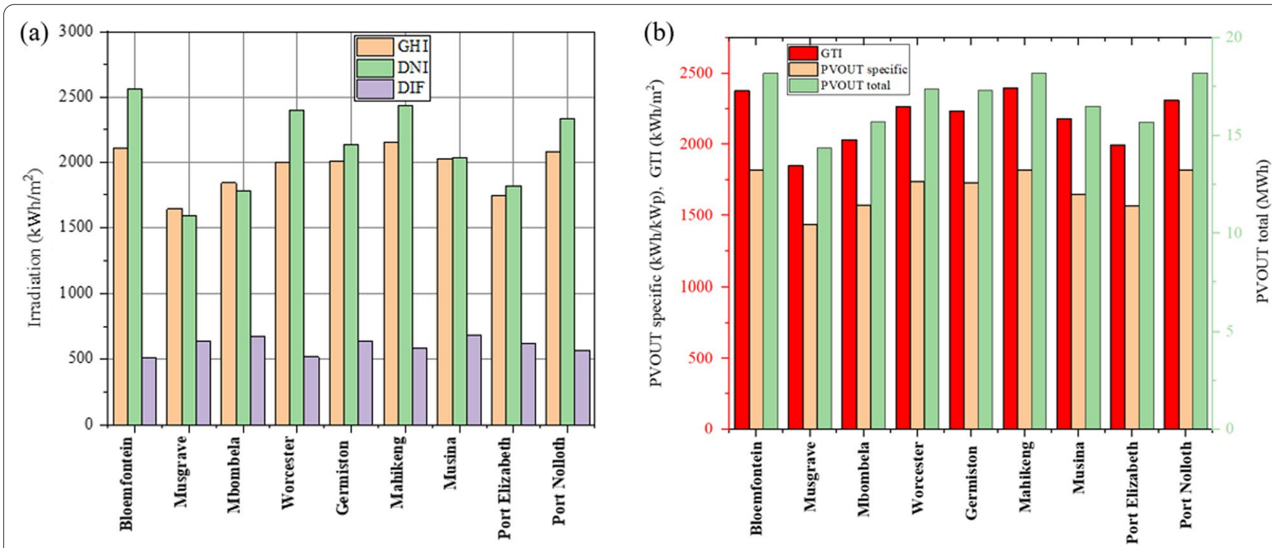

Fig. 7 Profile of yearly **a** insolation; **b** PV power output and GTI of the different site locations in South Africa

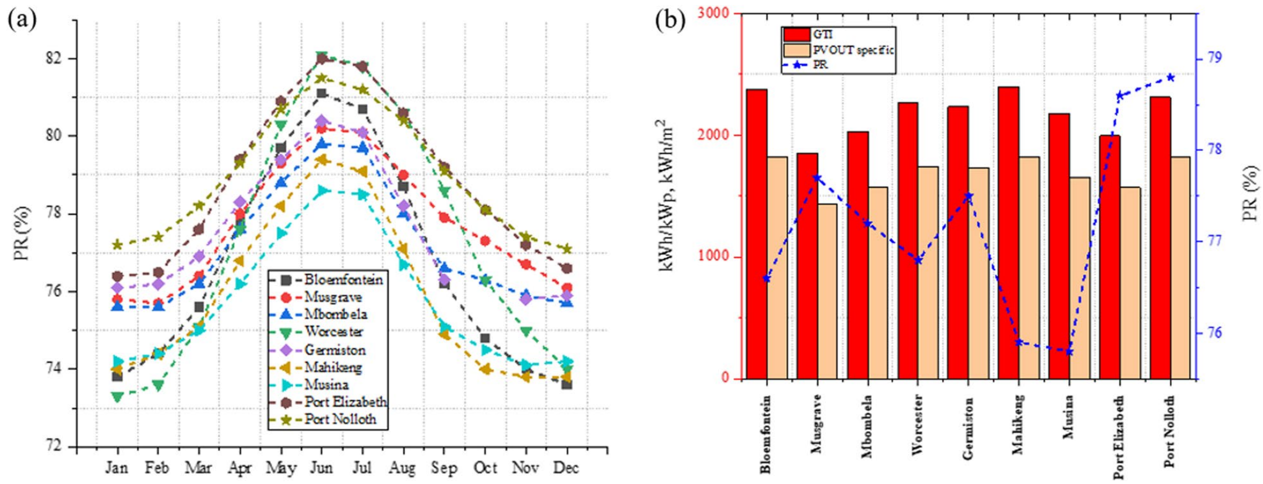

Fig. 8 PV system sites' **a** solar PV PR profiles; **b** the PR, GTI, and the specific PV power output

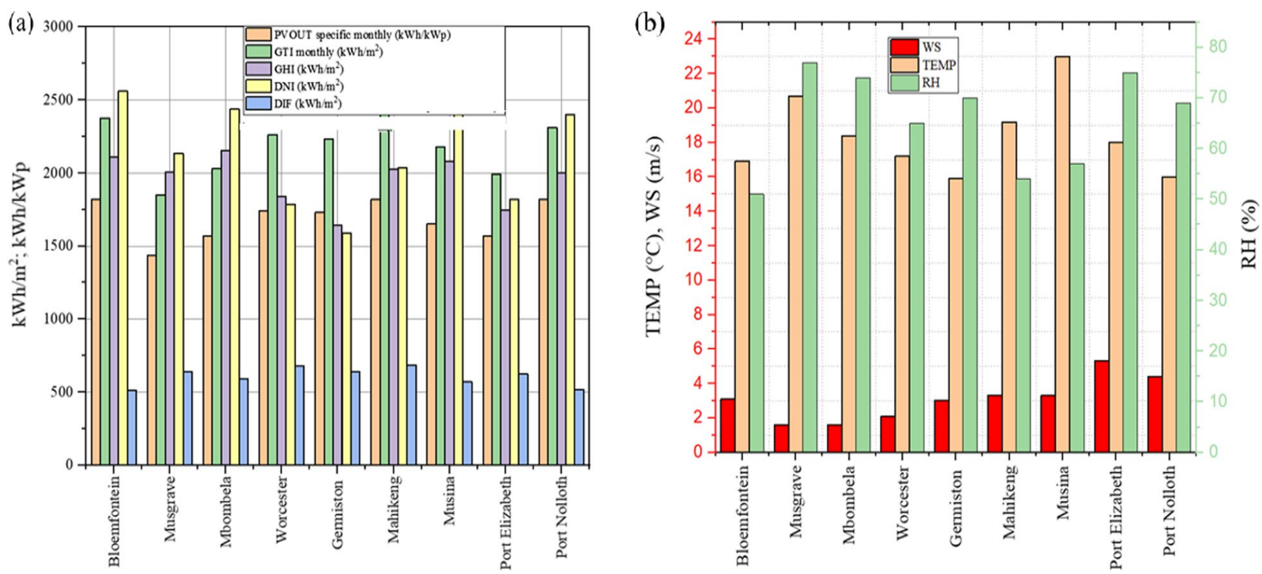

Fig. 9 Selected locations' **a** PV power potential, **b** PV power output limiting parameters

degradation; potential induced degradation (PID); all the system losses, such as mismatch and wiring losses; light-induced degradation (LID); soiling losses, inverter and transformer losses, system downtime and many more (Shiva Kumar and Sudhakar 2015; Quansah et al. 2017). Performance ratio, final PV system yield (Y_f), and reference yield (Y_r) are linked by the expressions given in Table 4.

The value of PR is usually lesser in the summer than in the winter and is between 60 and 80% due to the losses to the PV modules caused by elevated temperature in summer (Adrada Guerra et al. 2017). The PR of a given PV system and the site can be generated using PV design and simulation software applications. In this study, the profiles of solar PV PR of the selected PV system and sites as obtained from Solargis Prospect are presented in Fig. 8a. The PR is a function of GTI and the specific PV power output, as linked by Eq. (1) in Table 4, and these parameters are diagrammatically presented in Fig. 8b. It was observed that the highest PR reported was not in the site with the highest insolation. The PR of the site with the highest insolation, Mahikeng, is relatively low (75.9%) compared to the PR at Musgrave (77.7%), which has the least GHI and

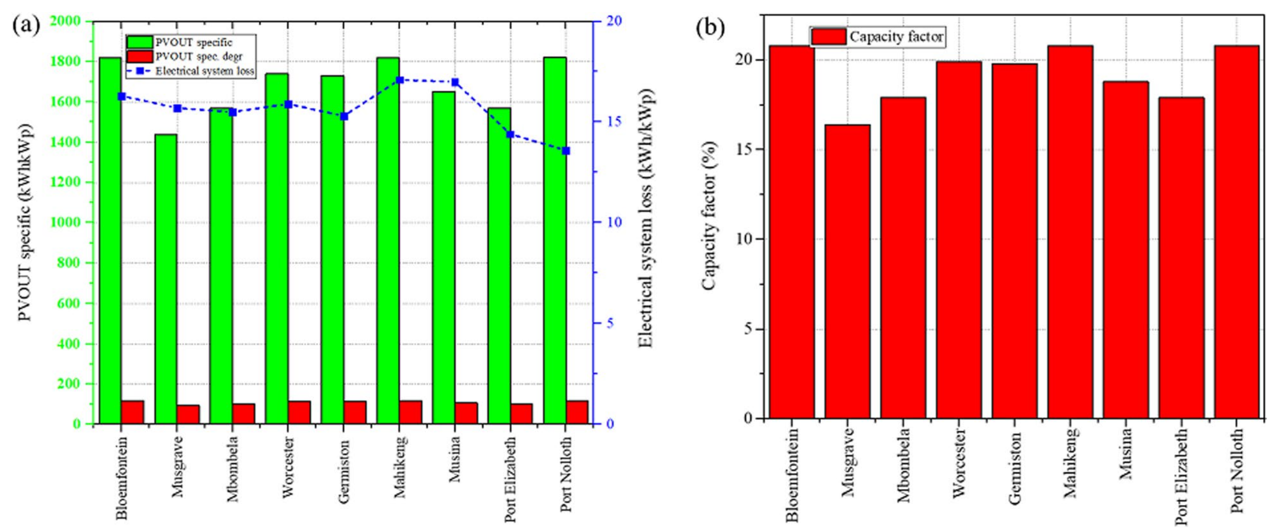

Fig. 10 **a** Energy-related losses; **b** capacitor factor

Table 4 Expressions linking PR (Atsu et al. 2021; Bansal et al. 2021; Shrivastava et al. 2021)

Parameters	Expression	Equation number	Unit
Performance ratio (PR)	$PR = \frac{PV_{outspecific}}{GTI} = \frac{Y_f}{Y_r} = \left(\frac{E_{out}}{P_o}\right) \Big/ \left(\frac{H_i}{G_{i,ref}}\right)$	(1)	Dimensionless
Final PV system yield (Y_f)	$Y_f = \frac{E_{out}}{P_o}$	(2)	(kWh/kWp')
Reference yield (Y_r)	$Y_r = \frac{H_i}{G_i}$	(3)	(kWh/kWp)

Here, $PV_{OUTspecific}$ is the specific photovoltaic power output (kWh/kWp); GTI is the global tilted irradiance; G_i is the sum of direct, diffuse, and ground-reflected irradiance incidents upon an inclined surface parallel to the plane of the modules in the PV array, H_i is the in-plane irradiation kWh/m^2, E_{out} is the energy output from PV system (AC) (kWh); P_o is the array power rating, AC (kW)

GTI values. However, the range of PR (75.8–77.7%) recorded across the nine sites, met the benchmark of an acceptable PR.

Here, GHI is the global horizontal irradiation; DNI is the direct normal irradiation; DIF is the diffuse horizontal irradiation; GTI is the theoretical global tilted irradiation; PVOUT specific and PVOUT total are specific and total PV power output, respectively; PR is the performance ratio.

Solar PV potential limiting factors

The performance of the solar PV system does not only depend on the level of irradiance but there are other factors, such as soiling, wind speed (WS), modules' partial shading, dust and dirt, ambient and cell temperatures, relative humidity (RH), and design flaws. These ambient-based and human factors can facilitate other performance limiting elements within the system, which include mismatch loss, power loss due to the degradation, direct current (DC) and alternate current (AC) wiring ohmic drops, and faults. This is due to deviation from the solar PV module's Standard Test Conditions (STC), defined as a module temperature of 25 °C, solar radiation G of 1000 W/m^2, and air mass (AM) of 1.5. Hence, this study will focus on RH, WS, and ambient temperature as it relates to irradiation and PV output.

Effect of ambient temperature

When the temperature of the module rises more than the STC value, the open circuit voltage is affected and the module short circuit current increases slightly. For instance, only 15–20% of the solar irradiance absorbed by rooftop silicon wafers PV panel is converted into electricity. The remaining 85–80% is a waste accounting for the heat energy causing working temperature increase in PV panels (Zhang et al. 2014), which triggers the system's voltage drop (Chaaban 2018). The performance conversion of a PV module drops by 0.40–0.50% for a degree rise in temperature (Natarajan et al. 2011). The lifetime of crystalline silicon cells and thin film modules PV panels are degraded by consistent hot, humid weather, while the efficiency of PV panels is improved by cooler PV panel temperatures.

Influence of RH and WS

Empirical study has shown RH on PV system's performance that a rise in relative humidity reduced current greatly (Njok and Ogbulezie 2018). Rays of sunlight are deflected or refracted by water vapour or droplets of water that collect on PV panels and this reduces the amount of irradiation reaching them and electricity production. Since elevated temperature impedes the flow of current but the wind is a coolant that lowers the PV panel's temperature. The efficiency of solar PV panels is 0.05% enhanced by a 1 °C temperature reduction (Solar. Com. 2022).

Energy system degradation and losses

The ageing of PV system components is another significant factor that contributes to energy losses and degradation, which require attention in the design of a PV system. This gives much lesser output by the panel than the solar power received. The estimation of degradation rate (DR) and light-induced degradation (LID) are essential in the prediction of PV systems' performance. High levels of humidity facilitate the bonding of dust on the surface of a panel and elevated ambient temperature in the presence of saltwater accelerates the degradation of module materials.

Typically, there is a difference between PV system power output and the installed capacity; and the capacity factor (CF) is normally used to describe the degree of this difference. The CF is simply the ratio between energy produced over a specified period (usually yearly) and the installed capacity. The ratio is from 10 to 25% because the installed capacity of a PV system is usually more than its output (WhatNextNow 2022). This occurrence determines the exact power output of a PV system challenging. Solar PV system losses, energy potential, nature of renewable energy and site location account for the CF. It is mathematically expressed as:

$$\mathrm{CF} = \frac{100 * \text{actual output}}{\text{Potential output}} \tag{1}$$

In this study, the yearly losses of specific PV power output and electrical system as obtained in Solargis Prospect are presented in Fig. 10.

Discussion

The solar PV system is energised by solar radiation, and therefore, accurate solar radiation analysis is one of the required rudiments that ensure a precise prediction of solar energy harvest and PV system performance. The uncertainty and variability that characterised solar radiation estimate of a given location is a complex process. This process has been simplified by several software applications, such as Solargis Prospect, and PVsyst. They deployed to design, assess, and evaluate the performance of a specified installed capacity of the PV system at a chosen location (Ashok Kumar et al. 2020; Dahmoun et al. 2021; Freitas Moscardini Júnior and Rüther 2020; Sukumaran and Sudhakar 2017). The summary of the findings obtained from this study is presented in Table 5. The estimates of relevant radiation and meteorological parameters that are used to measure the solar potential of the nine chosen sites are presented in Table 5.

The efficiency and PV power output of a defined PV system depend on on-site location, solar insolation, PV panel azimuth and tilt angles, types of PV cell material, such as monocrystalline and polycrystalline, amorphous silicon, and micro-amorphous silicon (Iqbal and Iqbal 2019). Aside from this, PV panels are often stressed during their operating lifetime; this is caused by their interaction with environmental elements that trigger panel degradation. These external elements include temperature, WS, RH, ultraviolet (UV) irradiation, and soiling due to dry build-up of various types of aerosols

Table 5 Radiation and meteorological parameters

Site locations	Solar radiation and meteorological parameters (yearly estimates)				PV power output parameters (yearly estimates)			
	GHI (kWh/m^2)	DNI (kWh/m^2)	DIF (kWh/m^2)	TEMP (°C)	PVOUT specific (kWh/kWp)	PVOUT total (MWh)	GTI (kWh/m^2)	PR (%)
Mahikeng	2156	2436.5	588.6	19.2	1819.3	18.193	2397.1	75.9
Bloemfontein	2111.5	2559.3	512.5	16.9	1819.4	18.194	2376.1	76.6
Port Nolloth	2082.3	2332.2	569.5	16	1820.5	18.205	2311.5	78.8
Musina	2026.1	2035.1	686	23	1649.8	16.498	2177.6	75.8
Germiston	2006.8	2134.4	640.4	15.9	1730.1	17.301	2233.2	77.5
Worcester	2003.2	2402.2	517.5	17.2	1739.6	17.396	2263.7	76.8
Mbombela	1839.9	1785.3	677.7	18.4	1569.2	15.692	2032.3	77.2
Port Elizabeth	1748	1820.7	623.1	18	1567.3	15.673	1993.6	78.6
Musgrave	1645.1	1590.4	640.4	20.7	1436.6	14.366	1849.2	77.7

(Lara-Fanego et al. 2018). The influence of these factors depends on the quality of module components, the nature of contact with single and the combination of the elements. For instance, the low levels of limiting factors are responsible for the relative high PV power output in Bloemfontein while the reverse is the case in Musgrave. As depicted in Fig. 9, the high levels of PV power limiting factors, such as RH and temperature are responsible for the low power output produced by the site in Musgrave.

Considering the impacts of RH, WS, and temperature on the PV system's performance following the information abstracted from the simulation report, Bloemfontein in Free State, leads in PV potential, as depicted in Fig. 9a. This corresponds to the lowest values of limiting factors, air temperature and RH, which are relatively low in Bloemfontein, as shown in Fig. 9b. Musgrave and Port Elizabeth in KwaZulu-Natal and Eastern Cape, respectively, possess relatively the lowest PV potential and highest magnitudes of PV performance limiting factors, such as temperature and RH, as presented in Fig. 9b.

The solar PV system usually experiences several conversions, and there are losses associated with this transition before the final output is released. It is either most of the energy that gets lost during transformation within the components or in the transfer through the wires. It was observed from the reports, as shown in Fig. 10a that the sites in Bloemfontein, Mahikeng, and Port Nolloth have the highest specific PV power output loss (118.8 kWh/kWp) and capacity factor (20%). In the same vein, the Site at Musgrave shows the lowest specific PV power output loss (93.8 kWh/kWp) and capacity factor (16.4%), as shown in Fig. 10b. The highest electrical loss (17 kWh/kWp) was at sites in Mahikeng, Musina and Port Nolloth, while the lowest (13.6 kWh/kWp) was at Port Nolloth.

Conclusions

Solar radiation along with other meteorological and weather parameters is usually processed based on typical meteorological years and applied in the design of various PV systems (Bre et al. 2021). The process is complex, and several models and software applications have been developed to facilitate accurate design and prediction of solar energy systems and examples some of these applications are Solargis Prospect, PVsyst, PV*SOL. The efficiency and PV power output of a defined PV system depend on the following parameters—location, solar irradiance, PV panel azimuth and tilt angles, and type of PV cell material (such as amorphous silicon, micro-amorphous silicon, monocrystalline, and polycrystalline). Additionally, the parameters such as temperature, WS, RH, soiling, and cabling losses affect both the efficiency and power output of a PV system.

A comparative assessment of solar PV energy potential and PV system performance of the different sites located in the nine provinces of South Africa was investigated in this study. The locations of the nine selected sites are Bloemfontein (Free State), Germiston (Gauteng), Mahikeng (North-West), Mbombela (Mpumalanga), Musgrave (Kwazulu-Natal), Musina (Limpopo), Port Nolloth (Northern Cape), Port Elizabeth (Eastern Cape), and Worcester (Western Cape). The hypothetical installed capacity of the monocrystalline silicon solar PV system used in this study is 10 kWp. This study portrays some valuable insights into the ability of monocrystalline rooftop PV systems, to provide clean energy, to meet the household need. The assessment report shows that:

1. GHI was lowest (1645.1 kWh/m^2) in Musgrave and highest (2156 kWh/m^2) in Mahikeng and their corresponding PV power output estimates follow the same trend.
2. The site in Mahikeng has the highest GHI 2156 kWh/m^2, and a corresponding specific PV power output (1819.3 kWh/kWp), closely followed by Bloemfontein (2111.5 kWh/m^2, 1819.4 kWh/kWp) and Port Nolloth (2003.2 kWh/m^2, 1820.5 kWh/kWp).
3. The lowest GHI (1645.1 kWh/m^2) and specific PV power output (1436.6 kWh/kWp) were recorded in Musgrave. The range of performance ratio (PR) of 75.8–77.7%) reported across the nine sites met the acceptable benchmark of PR.
4. The highest specific PV power output loss, 118.8 kWh/kWp, was obtained at sites in Bloemfontein, Mahikeng, and Port Nolloth, while the lowest, 93.8 kWh/kWp, was in Musgrave.

Additionally, from the results, it was observed that the range of:

1. The yearly average global horizontal irradiation (GHI) among the sites is 1645.1–2156 kWh/m^2.
2. The yearly average direct normal irradiation (DNI) among the sites is 1785.3–2559.3 kWh/m^2.
3. The yearly average diffuse horizontal irradiation (DIF) among the sites is 512.5–686kWh/m^2.
4. The yearly average global tilted irradiation (GTI) among the sites is 1849.2–2397.1 kWh/m^2.
5. The yearly average temperature (TEMP) among the sites is 16–23 °C.
6. The yearly average specific PV power output (PVOUT specific) among the sites is 1436.6–1820.5 kWh/kWp.
7. The yearly average total PV power output (PVOUT total) among the sites is 14.366–2397.1 MWh.

8. The yearly average performance ratio (PR) among the sites is 75.8–77.7%.

Based on the solar resource and performance results of the PV system obtained, the deployment of monocrystalline solar PV technology in all the considered sites across South Africa is technically viable.

Future study

The proof of the results is limited by the lack of verified insolation and PV power output data. Hence, the extension of this work should include:

1. An empirically based step to validate the simulation results.
2. The financial component of a PV system to establish its economic feasibility.

Abbreviations

CF: Capacity factor; DC: Direct current; AC: Alternative current; DIF: Diffuse horizontal irradiation; DNI: Direct normal irradiation; DR: Degradation rate; GHG: Greenhouse gas; GHI: Global horizontal irradiation; GTI: Theoretical global tilted irradiation; Impp: Actual amperage at MPPT; kWp: Kilowatt; kWh: Kilowatt-hour; LID: Light-induced degradation; Pmpp: Power at maximum power point; PR: Performance ratio; PV: Photovoltaic; UN: United Nations; PVOUT: Photovoltaic power output; RH: Relative humidity; SDGs: Sustainable development goals; SOC: State of charge estimating; STC: Standard test conditions; TEMP: Temperature; Umpp: Voltage at the maximum power point; UV: Ultraviolet; WS: Wind speed.

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Author contributions

WSE designed and carried out the computational analysis and drafted the manuscript, and PYT supervised and proofread the manuscript. All authors have read and approved the manuscript.

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