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Evaluation of Critical Solar PV Meteorological and Performance Parameters of a Roof-Mounted Crystalline Solar PV System in Berea, Durban, South Africa

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Abstract

The technical challenges that make solar photovoltaic (PV) less suitable for some applications include weather conditions, low energy densities, and low conversion efficiency. However, the effects of these shortcomings can be limited through a 3-stage solar PV system assessment and performance evaluation process in this study. The system installation is on geographical coordinate -29.85°, 031.00° at Musgrave, Berea, Durban, South Africa. Four solar PV assessment, design, and simulation software applications (PV*SOL, SOLARGIS Prospect and pvPlanner, and PVsyst) were deployed. Based on the simulation reports obtained from the four software applications used, the following estimates of solar potential assessment parameters were obtained - global tilted irradiation GTI, (1890 kWh/m^2); global horizontal irradiation, GHI (1684 kWh/m^2); diffuse horizontal irradiation DIF, (694 kWh/m^2); ambient temperature (19 °C). In addition, the following performance parameters were reported - produced energy (13.06 MWh/year); specific production (1511 kWh/kWp/year); performance ratio, PR (79 %); and solar fraction, SF (36.92 %).

Keywords: Renewable Energy, PV Performance Parameters, Solar Photovoltaic (PV), PV Assessment Parameters, PV Design and Simulation Software, PVsyst, PV*SOL, Solargis pvPlannar, Prospect.

Type: Research Article

1. Introduction

The environment and human health have been compromised in the quest of adequate energy for socio-economic development, with consequential climate change triggered issues, such as drought, flood, cyclones, rising temperature, increasing morbidity and mortality. These negative outcomes are more devastating in the Global South (Akinyele et al. 2020; Antwi and Ley 2021), especially in sub-Sahara Africa (SSA), where access to energy is very low. The most exploited energy sources are fossil and biomass. More than 90% of the households in about 25 countries of SSA rely on waste, wood, and charcoal for cooking. The consequential outcomes of these practices are drudgery, fire outbreaks, burns, GHG emissions, fume poisoning, economic impediment, respiratory diseases, and premature deaths. Despite these unhealthy trends arising from the high consumption of fossil fuels, and the gradual decline in the cost of PV panels, the deployment of solar PV systems is still in infancy in SSA. Several factors accounting for this include the inability to afford the high up-front capital costs, due to the level of poverty in the region; inadequate technical personnel development; insufficient awareness of solar merits, and ineffective end-users financing programmes and information (Amankwah-Amoah 2015; Ebhota and Tabakov 2020).

Aside from these socio-economic and political limiting factors, PV also has challenges of low energy densities and low conversion efficiency (Gürtürk, Benli, and Ertürk 2018; Ouédraogo et al. 2021; Xu et al. 2021). These demerits cause the PV system power supply to be intermittent, making it less suitable for applications. In addition, inaccurate assumptions of solar resources and sizing of the system can lead to system's over-sizing or under-sizing, higher cost, and a rise in erratic power supply. Hence, an accurate feasibility study of the solar potential of the site, and sizing of a solar PV system is a panacea to these shortcomings. Previously published studies on solar PV of the region under this study are mainly on the significance and potential of solar PV energy (Charles et al. 2019; Kunene et al. 2013; Mutombo and Numbi 2019; Zawilska and Brooks 2011). Studies on solar PV systems performance evaluation in Durban could not be found. Four major journal article search platforms, which include Google, Springer, ScienceDirect, and Wiley Online Library were used to search for previously published articles on solar PV potential and system performance assessment with the following keywords - solar PV in Durban, South Africa; solar PV assessment in Durban, South Africa; and solar PV system performance assessment in Durban, South Africa.

The provision of clean, affordable, and adequate energy for all by 2030, in compliance with the seventh item of the Sustainable Development Goal (SDGs) (UN 2015), greatly relies on the correct application of renewable energy technologies (RET). The focus this study is to provide PV potential and performance technical information that will aim for accurate application of PV technology by offering PV system's sizing technical guides to installers and investors. Additionally, the outcome of this study will be vital to policymakers in formulating the relevant framework to boost the provision of clean electricity. Therefore, in this study, the solar PV potential of a site at Steve Biko, Berea, Durban, South Africa, will be assessed and the performance of an installed capacity evaluated and reported. The assessment and performance appraisal of the proposed PV system will be determined through some key PV meteorological and performance parameters, such as global horizontal irradiance (GHI), performance ratio (PR), and rate of energy production. Some of the research questions that will be answered in this study are:

i. What is the possible annual energy generation of the planned PV system?
ii. Based on an annual estimate of the system, what is the energy loss due to light-induced degradation (LID), and an inverter?
iii. At start-up, what is the energy output, energy loss, PR, technical availability, and losses due to snow?
iv. What is the influence of relative humidity (RH) on insolation?
v. Considering the influence of technical availability and losses, what is the energy output specific, energy gain/loss, and PR?
vi. What is the theoretical and cumulative DR?
vii. What is the capacity factor (CF)?
viii. What is the rate of degradation of the PV system?

To address the set objectives satisfactorily, the paper is expressed in the following five sections: Section 1-2, deals with the background; Section 3, describes the methodology and PV simulation tools used and section 4 presents the simulation results and analysis in terms of performance, in comparison with the existing literature. Finally, the critical points will be highlighted, and the conclusion will be drawn in section 5.

1.1. Photovoltaic system

The solar radiation emitted in the form of light can be converted into usable electricity using a photovoltaic system. The photovoltaic system comprises an arrangement of many components (Al-Waeli et al. 2019), such as solar panels (PV cells) - that absorb and transform sunlight into electricity, as shown in Figure 1(a); an inverter - converts the output from direct current (DC) to alternating current (AC); and other materials to set up a working system - cabling, mounting, and electrical accessories. Once the PV cells in the solar panels absorb light, the photons of the light release energy to the electrons and this propels the electrons to flow as a current through the material (Ebhota and Jen 2018), as shown in Figure 1. The solar cells of commercial PV panels are mostly mono or polycrystalline silicon cells.

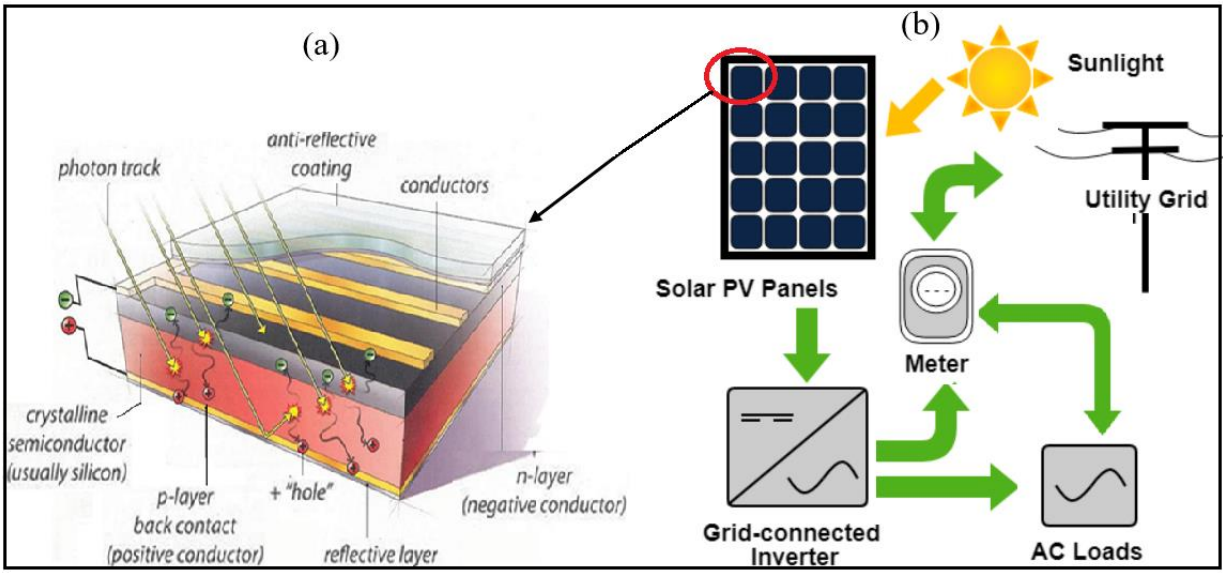

Figure 1: Schematic of a crystalline silicon solar cell (Apricus 2021)

1.2. Solar PV system design

In today's practice, several user-friendly engineering software applications have been developed to assess solar resources, model, simulate, and optimise solar PV systems. This has helped to overcome many of the complex activities involved in the assessment, design, and optimisation of PV systems and operations. In the Northern part of India, Chandigarh, a predictive study of energy loss, performance ratio (PR), capacity factor (CF), and degradation rate (DR) was conducted using PVsyst software application. The study considered a 200 kW, roof-integrated crystalline, installed at IRB Complex-5 (Kumar et al. 2019). The paper reported the estimated yearly performance parameters of energy losses, CF, PR, and DR as −26.5%, 16.72%, 77.27%, and −0.6 to −5%, respectively. In another study, PVsyst software was used to evaluate the potential and performance of a stand-alone photovoltaic (SAPV) system, installed at Kangar, Perlis, Malaysia. The total electrical energy produced and the types of energy losses by the PV system were estimated. Several other solar PV location-based studies using PV software applications are presented in Table 1.

Study	Location	Aim	PV cell type	PV software used
(Tarigan, Djuwari, and Purba 2014)	Surabaya	Computation of household PV system	C-Si	SolarGIS–pvPlanner
(Dahmoun et al. 2021)	Algeria	Evaluation of grid-tied large scale PV system performance and analysis		PVSyst
(Sukumaran and Sudhakar 2017)	Cochin International Airport Limited (CIAL), India	Operational performance analysis of 12 MWp solar PV for powering airport	Poly-c-Si	PVSyst and SolarGis
(Tarigan, Djuwari, and Kartikasari 2015)	Surabaya, Indonesia	Feasibility study of a grid-connected PV system installed in a residential area	Mono-c-Si	PVsyst and RETScreen
(Ramadan and Elistratov 2019)	Syria	Techno-economic feasibility study of a 300 kW grid-connected solar PV plant	Mono-c-Si	PVsyst
(Matchanov et al. 2020)	Tashkent	Characterisation of a 2.24 kW grid-connected micro-inverter type PV system	Poly-c-Si	PVsyst
(Owolabi et al. 2019)	Nigeria	To validate the techno-economic and environmental sustainability of installing a grid-connected solar PV system in Nigeria	mono-c-Si	RETScreen
(Touahri et al. 2020)	Kabertene, Adrar, Algeria	Evaluation of a 3 MW smart grid-connected PV system	Poly-c-Si	PVsyst
(Ali and Khan 2020)	Lahore University of Management Sciences (LUMS), Lahore, Pakistan	Assessment of techno-economic analysis of 42 kWp PV systems of p-Si and CIS systems	mono-c-Si, Poly-c-Si, and thin-film CIS	VPSOL
Where mono-c-Si and Poly-c-Si are mono-crystalline silicon and polycrystalline silicon, respectively, a-Si is amorphous silicon, and CIS is copper indium selenide.				

Table 1: Deployment of PV software applications

2. Methodology

Four PV software applications will be deployed for the complement, comparison, and robustness of the study. Solar PV potential and system performance assessment and prediction will be extracted from the generated reports and analysed. In addition, a comparative overview of the report will be tabulated and discussed. In this study, a 3-stage solar PV system assessment and performance evaluation procedure, as shown in Figure 2, will be adopted. The first stage will involve the description of the site location and configuration of the proposed PV system. The required input parameters of this stage include the site location coordinate, proposed PV capacity, type of installation, type of solar PV cell, PV geometry, and inverter type. In the second stage, the inputted site and proposed PV system configuration information will be processed and used to estimate the site's solar PV potential and PV system performance parameters. The last stage will be the generation of reports based on the supplied site and PV system information, processed with PV assessment and design software applications.

The goal of this study is to estimate the PV potential of a site at Musgrave, Berea, Durban, South Africa, in terms of PV meteorological and the proposed solar PV system performance parameters. A hypothesised 8-kWp grid-connected PV system will be modelled and simulated utilising these PV software applications PVsyst, PV*SOL, Solargis pvPlannar and Prospect. Some of the parameters that will be generated are solar meteorological parameters (irradiance, PV electricity, relative humidity CF, energy production and losses, PR, and degradation rate of the PV system. In addition, the simulation outcomes will be analysed to know the viability of the project and the likely challenges.

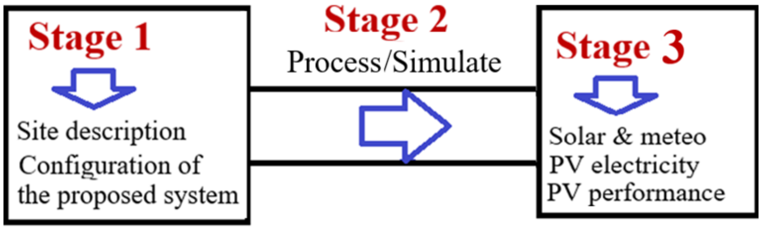

Figure 2: A 3-stage solar PV system assessment and performance evaluation procedure

3. Site Description and Configuration of the proposed PV System

This section has two subsections (3.1 and 3.2): where 3.1 focuses on on-site location description, while 3.2 deals with the configuration of the solar PV system, load profiling, and other basic design input parameters.

3.1. The site location

A hypothetical grid-connected solar PV system was selected for this study located on latitude -29.85° N, and longitude 31.00°' E, at an elevation of 238 m above the sea level in Musgrave, Durban, South Africa. Detailed information about the site location is required to estimate the solar PV potential. This is because the performance of the PV system depends on site-specific meteorological parameters, such as wind speed, ambient temperature, and solar irradiance characteristics. Other determinants include site factors, which include dust, latitude, pollution level, tree cover, and orientation. The chosen site is situated in an area known for both residential and commercial activities and a top view of the site is shown in Figure 3. Additional information on the system is presented in Table 2.

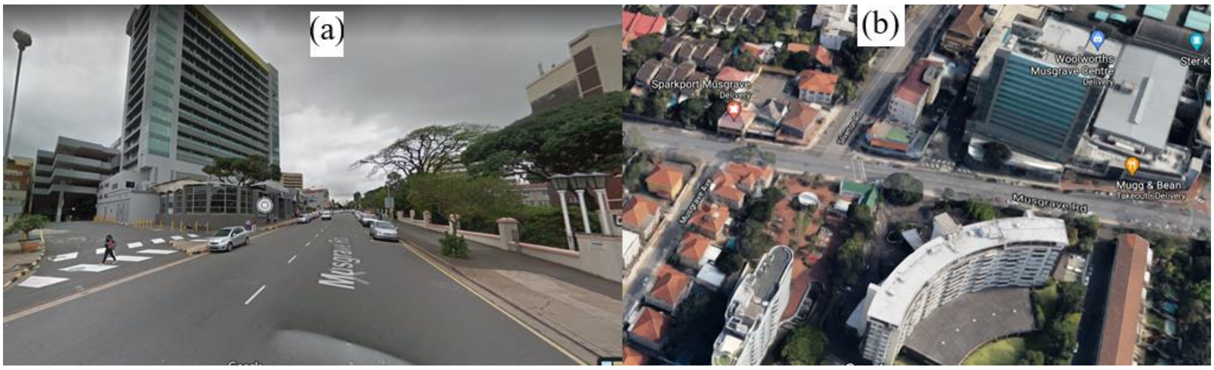

Figure 3: Musgrave, Berea, South Africa (a) Street view and (b) an aerial 3D view

Site location information	
Project name	Durban North
Address	89-121, Musgrave Rd, Berea, South Africa
Geographical coordinates (°)	-29.85, 31.00
Time zone	UTC+02, Africa/Johannesburg [SAST]
Elevation a.s.l (m)	83
Land cover	Urban areas
Population density (inh./km2)	2892
Terrain azimuth (°)	118
Terrain slope (°)	4
Slope azimuth (°) southwest	210
Annual air temperature at 2 m (°C)	20.9

Table 2: The site location and the system information

3.2. Solar PV system description

This study designs a hypothetically mounted 8.0 kWp-installed capacity of a tilted rooftop mount PV system on a residential building. The angle of tilt and Azimuth of the PV panels are such that the panels do not shade or overlap each other. The mounting of PV panels on rails that are attached to a tilted roof gives room for backside ventilation. A low-voltage grid connection, which is in a parallel circuit connection, through an inverter without storage is suitable for this type of PV system. Mono-crystalline 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 (Geotherm 2021; Sun et al. 2021). The solar grid-connected PV system in this study consists of the following major elements - PV panels, controller, inverters, utility meter, fuse box, and the gridlines. The solar PV modules generate direct current (DC) power and this is a product between the voltages and current. The inverter transforms the DC voltages into AC voltages.

The inverter's AC output is supplied to the grid through the utility meter and fuse box, respectively. In the grid-connected solar PV systems, the inverter usually attempts to operate in phase with the grid. A circuit breaker in a fuse box and the utility meter can be mounted on the output terminals of an inverter. Details of the PV modules and inverter information and other input parameters used in this study as obtained from PVsyst and Solargis PV software applications are presented in Table 3.

General information: Grid-connected			
PV field orientation		Models used	
Installation type	Roof mount	Transposition	Perez
Azimuth/inclination	0° (north)/30°	Diffuse	Perez, meteonorm
User's needs		Circumsolar	Separate
Fixed constant load (W)	571	Horizon	
Global (kWh/year)	5000	Free horizontal	No shading
PV array characteristics			
PV module		Total PV power	
Manufacturer	CSI Solar	Nominal (STC) (kWp)	9
Model	CS3K-320MS-AG	Total number of modules	27
PV module type	c-Si – monocrystalline silicon	Module area (m²)	45.6
Unit Nom. Power (Wp)	340	Cell area (m²)	40.5
Number of PV modules (units)	27	Inverter	
Designed system size (kWp)	8.0	Manufacturer	GESolar
Nominal (STC), kWp	9.18	Model	GES2-3K3TL
Modules 2 Strings x 10 In series		Unit Nom. Power (kWac)	3.00
At operating conditions (50°C)		Number of inverter units	3
Pmpp (kWp)	8.37	Total power (kWac)	9.0
U mpp (V)	274	Operating voltage (V)	150-450
I mpp (A)	31	Pnom ratio (DC:AC)	1.02

Table 3: System information

4. Solar PV System Design and Simulation: Results and Analysis

This section presents the system design and simulation results, and analysis. The defined parameters from both location description and the system information in section 4 serve as inputs for the simulation operation in this section. There are three main segments of this section: 4.1 - Solar potential assessment; 4.2 - Solar PV system performance evaluation; and 4.3 - Energy conversion and solar PV system losses.

4.1. Solar potential assessment

The simulation results of the solar potential assessment and power generation as regards the proposed PV system are presented and analysed in this section.

Solar insolation

The PV system is energised by solar insolation; therefore, solar irradiation is the most significant amongst the project-specific meteorological parameters that define solar electricity production potential (Wang 2019). Photovoltaic software, Solargis Prospect was deployed to assess both the monthly and yearly variations of solar GHI, DIF, and DNI of the selected site at Musgrave Road, Durban, South Africa. The estimates of the parameters to measure the solar potential of a given location are shown in Figure 4 (a-d). The assessment report shows that GHI was lowest in June and highest in January, estimated as 94.2 kWh/m^2 at 17.2 °Cand 177.3 kWh/m^2 at 23.9 °C, respectively, as shown in Figure 4(a). The site has seven months of relatively high GHI, from January – March, and September – December, and four months low of GHI, April – August, as shown in Figure 4(b).

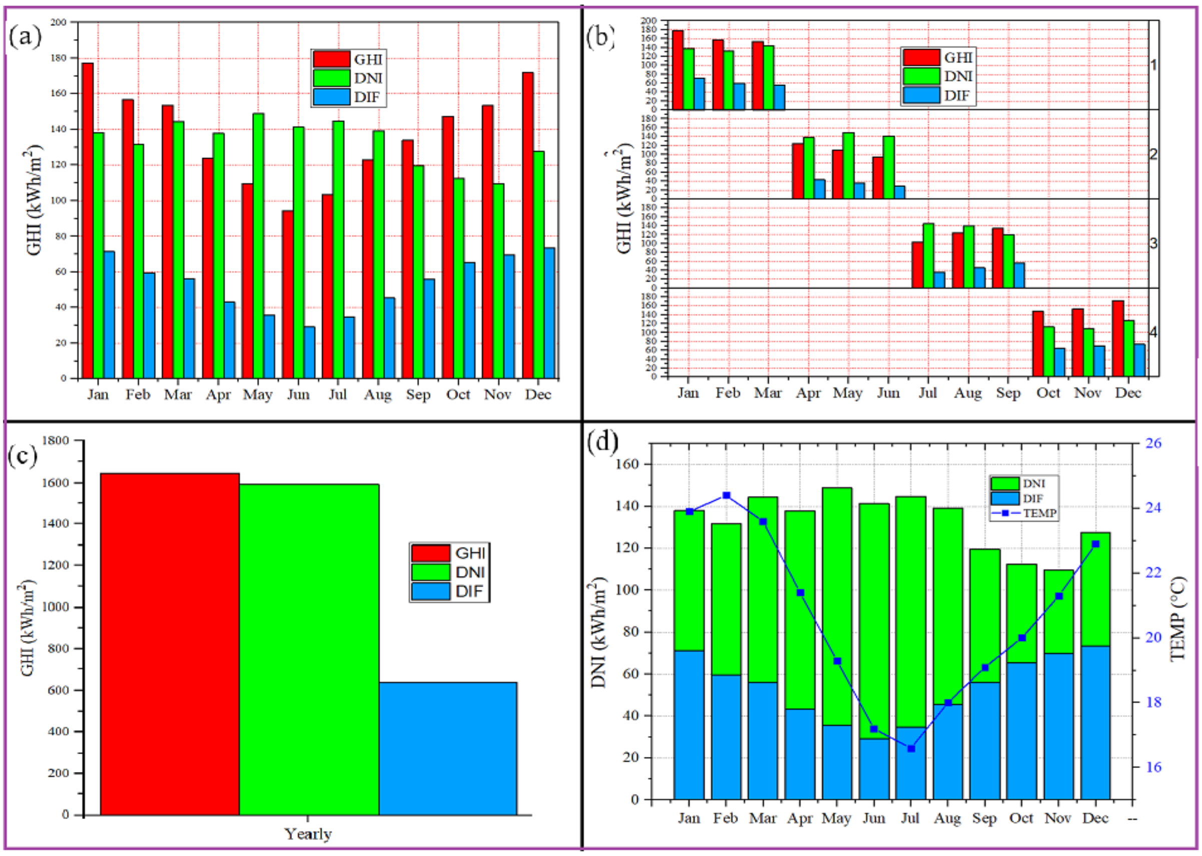

Figure 4(a-d): The estimates of solar monthly and yearly variations of GHI, DNI, DIF and ambient temperature of Musgrave, Durban, South Africa, obtained from Solargis Prospect

Other PV software applications along with Solargis Prospect reports were considered and analysed and some of the key PV meteorological parameters required for solar PV system performance prediction were extracted. The PV software applications used for the assessment are PV*SOL, PVsyst, and Solargis pvPlannar; and the information extracted from them is presented in Table 4.

Software	Highest GHI (kWh/m2)	Month	Lowest GHI (kWh/m2)	Month	Yearly average GHI (kWh/m2)	Yearly average T_Amb (°C)	Earray (MWh)	E_Grid
PVsyst	196.3	January	97.8	June	1759.5	20.58	16.004	13.037
Prospectus	177.3	January	94.2	June	1647.8	20.7	11.926	
pvPlannar	176	January	96.0	June	1646	20.8	11.4	
PV*SOL	190	January	110	June	1877	15.5	11.985	10.525
Average	184.9		99.5		1732.6	19.4	12.8	11.8
Where GHI is the global horizontal irradiation; Earray is the effective energy at the output of the array; E_Grid is the energy ejected to the grid; T_Amb is ambient Temperature.								

Table 4: Key meteorological parameters obtained from different software applications

In this study, four reports obtained from different PV software applications were harmonised and used in the assessment of PV potential and estimation of 8-kWp PV performance of a site at Berea, Durban. Subsequently, 1732.6 kWh/m^2/year, and 1646 to 1759.5 kWh/m^2/year, was being considered as the average and range of GHI, respectively, as depicted in Figure 5(a). Comparing the reports obtained from the various applications used, similarities were observed in the simulation results: they all reported January and June as the months of the highest and lowest GHI, respectively; PVsyst, and Solargis pvPlannar and Prospect reported an ambient temperature of about 21℃ while PV*SOL reported 15.5℃, and the GHI results maintain the same profile. The pattern of irradiance profile obtained supports the affirmation that solar PV generation largely depends on seasonal change.

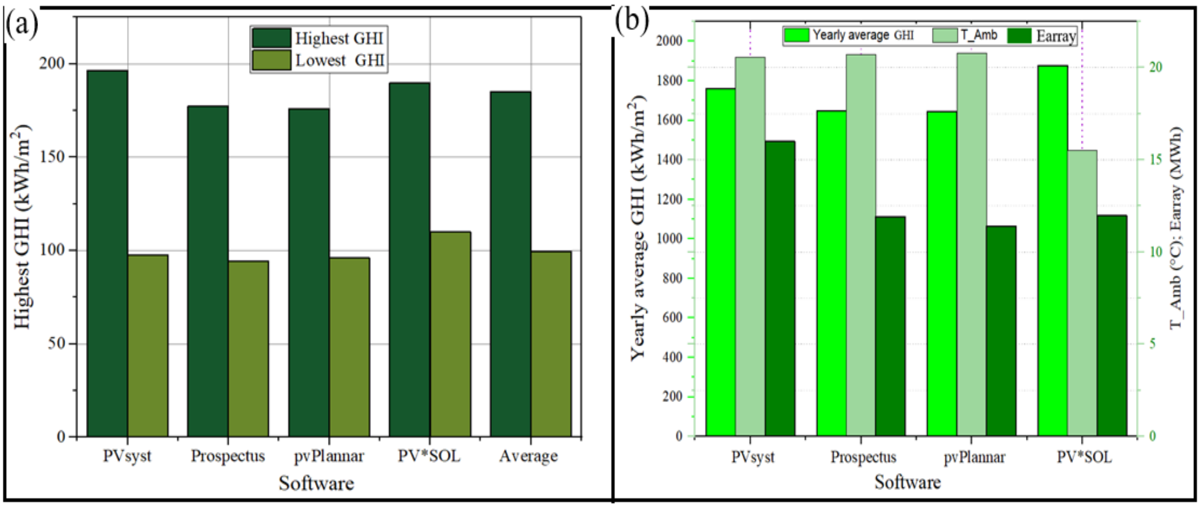

Figure 5: GHI a comparative chart obtained from PV*SOL, PVsyst, and Solargis Prospect and pvPlannar reports

4.2. Solar PV system performance evaluation

Some parameters are used to measure the performance of a solar PV system. These define the general system performance concerning energy generation, the overall effect of system losses, and solar resources. Additionally, they are used to make comparisons between systems as regards design, geographic locations, and technology. Some of these key performance parameters are performance ratio (PR), final PV system yield and losses, reference yield (Marion et al. 2005) and energy production, capacity factor (CF), and degradation rate of the PV system (Dubey et al. 2014; Peerapong and Limmeechokchai 2015; Phap et al. 2020; Purohit and Purohit 2018; Shiva Kumar and Sudhakar 2015). This will be discussed in the following subsections: 4.2.1-Energy generation; 4.2.2-Household consumption and feed-in grid; 4.2.3-Performance ratio (PR); Solar fraction; 4.2.4-Solar fraction; and 4.2.5-Capacity factor.

4.2.1.Energy generation

This section presents the maximum yearly energy production as obtained in the reports of the various software applications used. The PVsyst software reported the highest yield (16.004 MWh), followed by PV*SOL (11.985 MWh). The specific energy production has the same trend as the yearly energy production. The average of the yearly energy production reported by four applications used is 12.829 MWh, as shown in Figure 6(a). The highest specific energy production of 1663 kWh/kWp was obtained in PVsyst, while solargis Prospect reported the lowest of 1423 kWh/kWp.

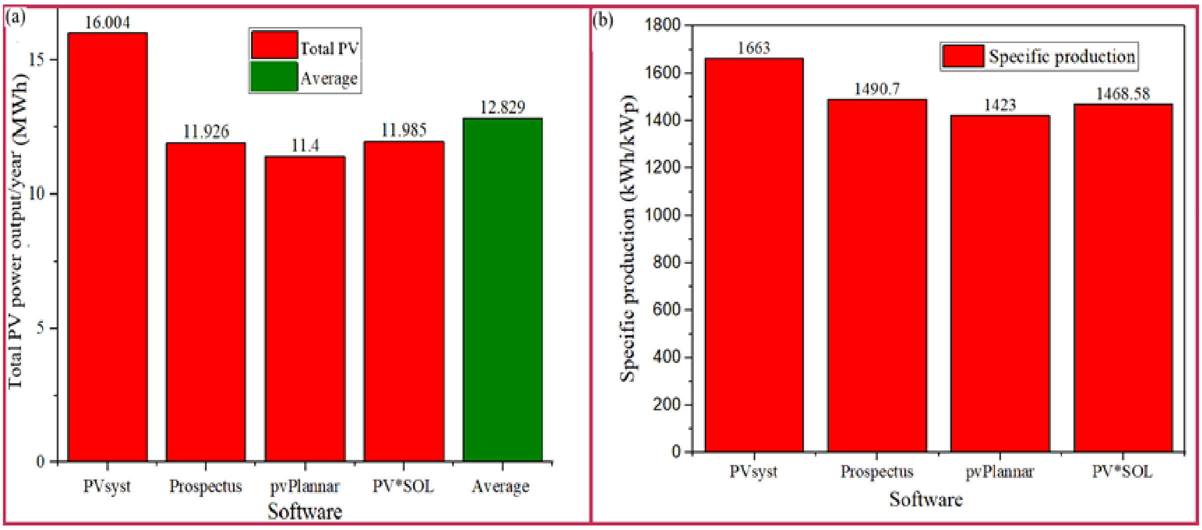

Figure 6: (a) the yearly energy production by the different software applications
(b) the reported PR by the different software applications

Considering the yearly energy PV production, the highest yield of about 16.004 MWh was reported by PVsyst, as presented in Table 5, while the maximum monthly yield is hovering between 1.0 and 1.15 MWh. All the software applications were unanimous in the minimum monthly yield of about 0.9 MWh in some months. Low ambient temperature (between 7˚C and 20˚C), low rainfall, and RH that are associated with winter, account for the high yield recorded in May to August. The cloudy or frequent rainfall and relatively high ambient temperature (between 15˚C and 29˚C) in summer are responsible for the low yield in November to March with the exemption of January. January, being the month with the longest day of sunshine is the reason for the energy high yield.

Software	Yearly energy prod (MWh)	Months max energy yield	Estimates of max yield monthly (MWh)
PVsyst	16.004	January, March, August	1.04
Prospectus	11.926	January, March, May, July, August	1.02
pvPlannar	11.4	January, March, April, May, July, August	1.0
PV*SOL	11.985	July, August	1.15

Table 5: Months of maximum yield as reported by the various applications used

Similarly, it was observed in Figure 7(b) that there is relatively high-energy consumption (above 400 kWh) in some months. The months with high consumption can be categorised into two groups: October − December and July − September. The high consumption in October – December is caused by longer day's activities that require power while the heavy electrical loads, such as water geyser and room heater usage during winter, account for the consumption in July – September.

4.2.2. Household consumption and feed-in grid

The annual energy production and feed-in grid obtained from PVsyst and PV*SOL simulation results are shown in Figure 7(a), and the monthly energy generation by the PV system and own consumption are shown in Figure 7(b). The total energy consumption projected for the household is 5000 kWh/year and it was observed in the PV*SOL's simulation result: that the solar system supplied 28.7%, about 1459 kWh. The grid will cover the remaining 70.82%, about 3541 kWh energy consumption for the household. The estimate of the energy produced yearly by the solar PV system is 11984 kWh and 12.2%, about 1459 kWh, of this will be supplied for own consumption. This implies that 87.8%, about 10525 kWh, of the annual generated energy will be fed to the grid, as depicted in Figure 7(c).

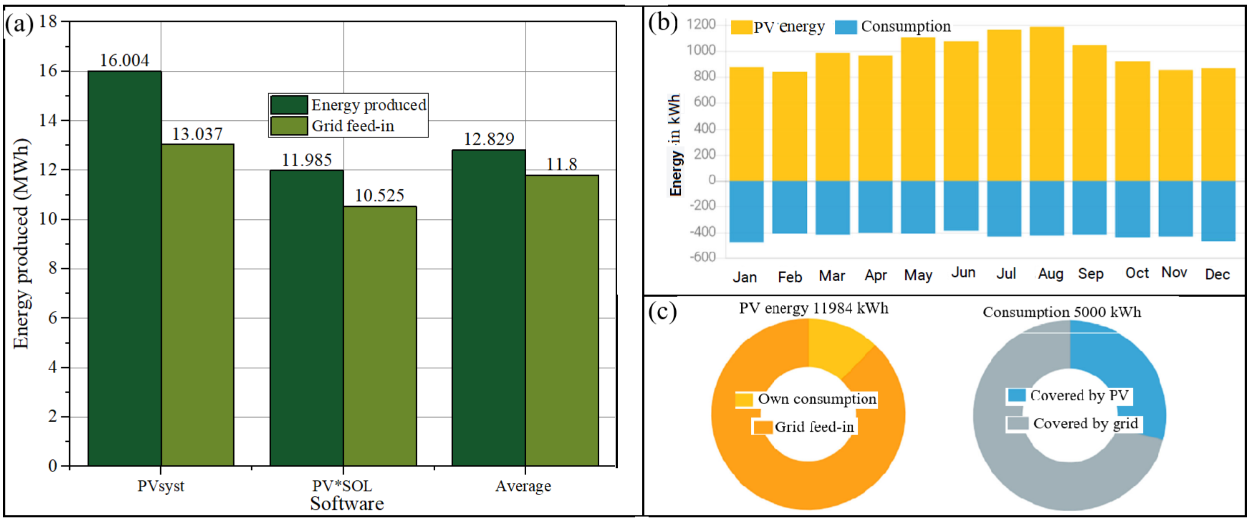

Figure 7: (a) Annual energy production and feed-in grid
(b) Own consumption and feed-in grid

4.2.3. Performance ratio (PR)

The PR is specific PV power output ($PV_{OUTspecific}$) divided by the global tilted irradiance (*GTI*). It is also defined as the ratio of actual energy output to theoretical energy output. The values of PR are generally computed and reported on either a daily, weekly, monthly or yearly basis and it is deployed to make a comparison between PV plants supplying the grid at different locations around the world. It measures PV system performance, taking into consideration factors of meteorology, such as relative humidity (RH), climate changes, temperature, and irradiation. The relationship between PR, Y_f, and Y_r is presented in Table 6.

The value of PR is usually between 0.6 and 0.8 and is lesser in the summer than in the winter, resulting from losses due to PV module elevated temperature, as depicted in Figure 8(b). Hence, the PR reported in this study is satisfactory, as the highest and lowest PR obtained are 83.49% and 75.5%, reported by PVsyst and Solargis Prospect, respectively, as depicted in Figure 8(a).

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

Table 6: Performance ratio concerning final PV system yield and reference yield

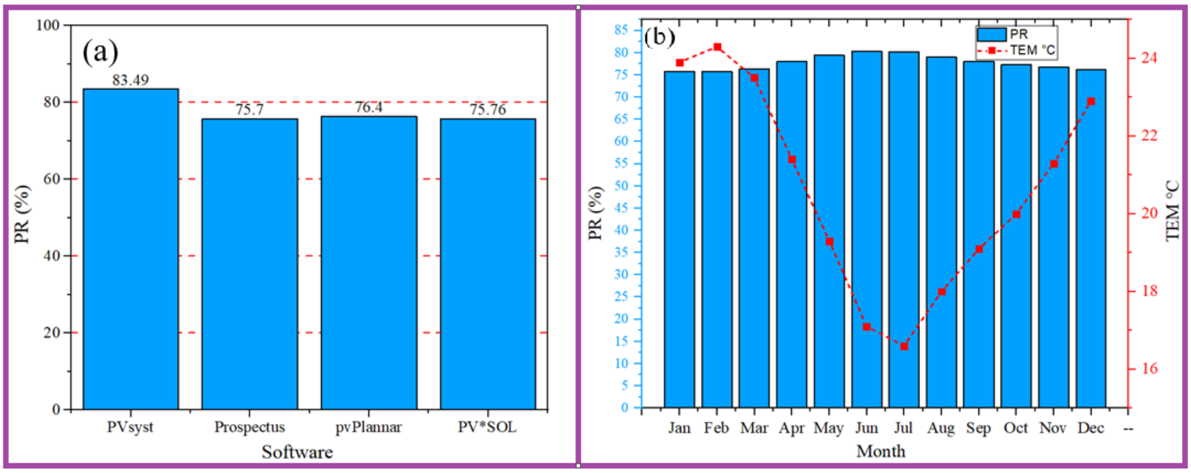

Figure 8: PR values by the different applications

4.2.4. Solar fraction

The solar fraction (SF) or solar savings fraction is the ratio of the quantity of energy supplied by the solar system to the total energy required. The value of SF is zero when there is no energy utilisation. The SF of a specified solar system depends on the following factors – the load, the operation, the collection and storage sizes, and the climate.

- ✓ In this study, two of the software applications, PVsyst and PV*SOL, estimated the proposed solar PV system as 44.64% and 29.2%, respectively.

4.2.5. Capacity factor

The power output of a PV system is usually different from the installed capacity and this makes finding the correct output of PV a system very challenging. The PV system output is usually less than the installed capacity. This implies that the ratio between the actual generated output over a given period and the possible maximum output as installed is usually less than 100%. This ratio is called capacity factor (CF) and is due mainly to the availability of the energy source and several other technical constraints, such as PV system losses, nature of renewable power, and site location. Capacity factor (CF) for solar PV systems variation depends on the location and at nature's mercy, and the range is about 10-25% (IEA 2018).

- ✓ In this study, 17% CF was recorded, as obtained from Solargis Prospectus.

4.3. Energy conversion and the solar PV system losses

The approximation of the total of the theoretical annual specifics of a solar PV system electricity production is presented in Table 7, as obtained from Solargis pvPlannar. This excludes the long-term ageing and PV modules' performance degradation. There are typical types of field losses that occur within the grid connection of PV frameworks throughout the year.

Energy conversion step	Energy output	Energy loss	Energy loss	PR	
	[kWh/kWp]	[kWh/kWp]	[%]	Partial %	Cumm %
Global in-plane irradiation (input)	1863	-	-	100.0	100.0
Global irradiation reduced by terrain shading	1851	-12	-0.7	99.3	99.3
Global irradiation reduced by reflectivity	1803	-47	-2.6	97.4	96.8
Conversion to DC in the modules	1584	-220	-12.2	87.8	85.0
Other DC losses	1497	-87	-5.5	94.5	80.3
Inverters (DC/AC conversion)	1459	-37	-2.5	97.5	78.3
Transformer and AC cabling losses	1437	-22	-1.5	98.5	77.1
Reduced availability	1423	-14	-1.0	99.0	76.4
Total system performance	1423	-440	-23.6	-	76.4

Table 7: System losses and performance ratio

The loss diagram offers a quick insight into the quality of a PV system design, and the losses represented in the diagram, as depicted in Figure 9, including module quality loss, temperature loss, conversion loss, soiling loss, wiring loss, and mismatch loss. The loss results obtained can be subjected to critical technical analysis for further enhancement of the system's efficiency.

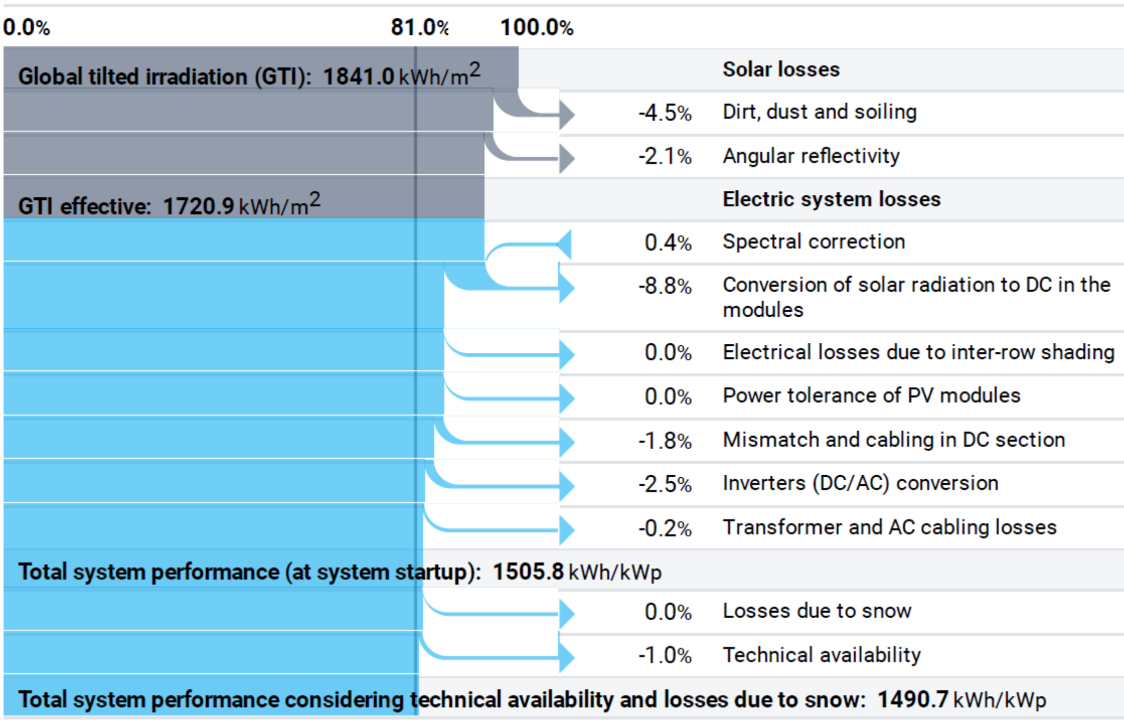

Figure 9: The theoretical losses due to energy conversion in the PV power system

5. Carbon Balance and the saved CO_2 Emissions

Fossil fuel dominated the space of energy sources for the generation of electricity. The exploitation of fossil fuels in building global economies over the decades came with both human and environmental challenges. This has been recognised and responded to with an outcry, seeking the reduction or stopping of the use of fossil energy (Ebhota 2019, 2021). The use of solar PV systems will limit carbon emissions since the deployment of fossil fuels for electricity generation contributes the highest share to CO_2 emissions. A net saving of CO_2 emissions is said to occur if the carbon footprint of the grid electricity production is more than the PV installation per kWh. Therefore, the overall amount of carbon balance for a PV system is the difference between the saved CO_2 and the produced emissions. Carbon balance depends on the following four main factors - energy yield, system lifetime, grid LCE, and PV system LCE.

Some PV system design and simulation applications, such as PVsyst and PV*Sol, are used to estimate the saved CO_2 concerning the installed PV capacity. In this study, the saved CO_2 emissions for the 8 kWp installed and the CO_2 balance for 30 years were calculated and reported using PVsyst, as presented in Table 8 and Figure 10. The evaluation of the saved CO_2 using the PVsyst carbon balance tool is based on life cycle emissions (LCE), which portrays the CO_2 emissions connected to a chosen part or energy amount (PVsyst 2021).

General emissions			
Total replaced emissions (tCO_2)	21.16	Lifetime (years)	30
System production (MWh/yr)	15.27	Annual degradation	1.0
Grid Lifecycle Emissions (gCO_2/kWh)	927		

System lifecycle emissions			
Item	LCE	Quantity	Subtotal [$kgCO_2$]
Modules	1713 kgCO2/kWp	10.2 kWp	17470
Supports	6.18 kgCO2/kg	300 kg	1855
Inverters	613 kgCO2/	3.00	1838

Table 8: Detail information of CO2 emissions

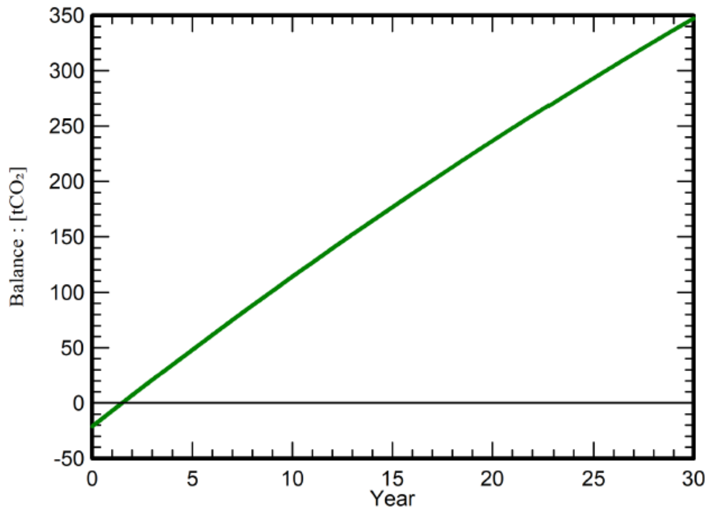

Figure 10: Saved CO_2 Emission vs. Time

6. Conclusion

Solar PV system is considered less suitable for certain applications because of the associated power supply intermittent. This, coupled with others shortcomings, such as inaccurate assumptions of solar potential, over-sizing and under-sizing of a system cause unrealistic project cost, erratic power supply, and failure. The aim of this study, therefore, is the assessment of solar PV Potential and performance prediction of a 6-kWp PV system, hypothetically sited in a location on the geographical coordinate -29.85, 31.00 at Musgrave, Durban, South Africa. The outcome of this study will provide information that facilitates accurate PV system sizing and offers technical guides to installers and investors. Additionally, this information is equally vital to policymakers in formulating the relevant framework to boost the provision of clean electricity.

A hypothesised solar PV system of mono-crystalline PV cells was used to evaluate the technical meteorological and performance parameters of a rooftop solar PV system to provide electrical power to a household and grid connection. The study was performed to determine both the PV resource potential of the site at Musgrave, Durban, South Africa, and to predict the performance of the 8-kWp mono-crystalline PV system. The study was carried out using PVsyst, SolarGIS-Prospect, SolarGIS-pvPlanner, and PV*SOL software applications. Potential assessment and performance parameters variations amongst the software applications used were observed and presented in Table 9.

Parameters	PVsyst	PV*SOL	SolarGIS-pvPlannar	SolarGIS-Prospect	Average value
Assessment parameters					
Global tilted irradiation, GTI (kWh/m2)	1992.2	1877	1851	1841.0	1890
Global horizontal irradiation, GHI (kWh/m2)	1759.5		1646	1647.8	1684
Diffuse horizontal irradiation, DIF (kWh/m2)	748.56			639.7	694
Air temperature, TEMP (°C)		15.5	20.8	20.7	19
Performance parameters					
Produced Energy (MWh/year)	15.27	11.98		11.93	13.06
Specific production (kWh/kWp/year)	1663	1469	1423	1491	1511
Performance, PR, (%)	83.49	75.76	76.4	81.0	79
Solar Fraction, SF, (%)	44.64	29.2			36.92

Table 9: Potential assessment and performance parameters variations

The differences in the source of climate data, design considerations, and model equations amongst the software applications deployed to account for these variations were noted. However, the lack of verified PV power output and insolation data limits the proof of the results. Despite the shortcomings, this study portrays some valuable insights into the ability of mono-crystalline rooftop PV systems, to provide clean energy, to meet the household need. Useful information obtained from the simulation results includes:

i. The average annual energy yield of the proposed system at Musgrave, Durban is about 13.06 MWh, of which 34% will be consumed and about 86% fed into the grid.
ii. The average PR of 79% of the solar PV system obtained is satisfactory for execution and commissioning.
iii. The simulation results show the technical viability of the proposed grid-connected rooftop PV system in Musgrave, Durban, South Africa, with the benefits of supplying clean energy that reduces the emission of CO_2.

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