Assessment of solar PV potential and performance of a household system in Durban North, Durban, South Africa

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Abstract
The potential of solar PV is location-dependent that needs to be assessed before installation. This study focuses on the assessment of a solar PV potential of a site on coordinates −29.853762°, 031.00634°, at Glenmore Crescent, Durban North, South Africa. In addition, it evaluates the performance of a 6-kWp installed capacity grid-connected rooftop solar PV system to supply electricity to a household. The results, obtained from PV design and simulation tools—PV*SOL, Solargis prospect, and pvPlanner, were used to analyze and establish the PV system’s economic and technical viability. The configuration of the system is as follows: load profile—a 2-person household with 2-children, energy consumption—3500 kWh, system size—6 kWp, installation type—roof mount, PV module type—c-Si—monocrystalline silicon, efficiency—18.9%, orientation of PV modules -Azimuth 0° and Tilt 30°, inverter 95.9% (Euro efficiency), and no transformer. The results show: meteorological parameters—global horizontal irradiation (GHI) 1659.3 kWh/m², direct normal irradiation (DNI) 1610.6 kWh/m², air temperature 20.6 °C; performance parameters—annual PV energy 8639 kWh, Specific annual yield 1403 kWh/kWp, performance ratio (PR) 74.9%, avoided CO₂ emissions 5662 kg/year, and solar fraction 42.5%. Others are economic performance parameters—levelised cost of energy (LCOE) 0.1147 USD/kWh, internal rate of return (IRR) 17.671 USD/kWh, and return on investment (ROI) 11%. The results show that the proposed solar PV system under the current conditions is both economically and technically viable for household electrification in Durban North, South Africa.

Graphical abstract
Keywords Renewable energy · Solar photovoltaic (PV) · PV performance parameters · PV potential assessment · PV system economic feasibility · PV*SOL and solargis

Abbreviations

ALB  Surface albedo  
CAPEX Capital expenditure  
CDD Cooling degree days  
CF Capacity factor  
D2G Ratio of diffuse horizontal irradiation and global horizontal irradiation  
DIF Diffuse horizontal irradiation  
DNI Direct normal irradiation  
GHI Global horizontal irradiation  
GTI Global tilted irradiation  
HDD Heating degree days  
IRR Internal rate of return  
LCOE Oevelised cost of energy  
NPV Net present value  
OPEX Operating expenses  
PPA Power purchase agreement  
PR Performance ratio  
PREC Precipitation  
PV Photovoltaic  
PVOUT Photovoltaic power output  
PWAT Precipitable water  
RH Relative humidity  
ROI Return on investment  
SNOWD Snow days  
TEMP Air temperature  
WS Wind speed  
Dirθ,α Direct insolation from the sun map  
θ Centroid at zenith angle  
α Azimuth angle  
SConst Solar constant  
β Transmissivity of the atmosphere  
SunDurθ,α Time duration represented by the sky sector  
SunGapθ,α Gap fraction for the sun map sector  
m(θ) Is the relative optical path length  
AngInθ,α Angle of incidence between the centroid of the sky sector and the axis normal to the surface  
Gz Is the surface zenith angle  
Gα Is the surface azimuth angle  
θ₁ and θ₂ Bounding zenith angles Sky sector  
Divazi Number of azimuthal divisions in the sky map  
PVOUTspecific Specific photovoltaic power output  
G₁ Mum of direct, diffuse, and ground-reflected irradiance incident  
H₁ In-plane irradiation  
Eout Energy output  
P₀ Array power rating  
Lc Array capture losses  
YR Reference yield  
YF Array yield  
GCC Clean reference solar cell irradiance  
GDC Dirty reference solar cell irradiance  
GL Soiling loss

Introduction

The continuous extensive use of fossil fuels is increasingly adding to the concentration of CO₂ in the atmosphere, which contributes to the global temperatures rise and environmental degradation (Almasoud and Gandayh 2015). The use of fossil fuel contributes the highest share to CO₂; a by-product of fossil fuel combustion, emitted into the atmosphere (Nachmany et al. 2014). The sacrificing of the environment and human health for the energy required for socio-economic activities continues. The International Energy Agency (IEA), reported that the global energy-related CO₂ emissions in 2019 was 33.4 GtCO₂ and dropped to 31.5 GtCO₂ in 2020 because of pandemic (IEA 2021). About 38.5% of the global CO₂ emissions come from the power sector (Worldmeter 2020). South Africa emitted about 456 MtCO₂ and contributed 1.3% of the global CO₂ emissions. The country ranked was 1st and 14th emitter of CO₂ in Africa and the world, respectively (Fleming 2019); about 60.5% of the emission comes from the power sector (Worldmeter 2021).

The present large economies are products of fossil fuels, such as natural gas, coal, and oil. These are unarguably effective economic boosters, but they leave behind negative environmental impacts and health consequences (Ebhota and Tabakov 2020). The consequential effects of the continuous use of these fuels to the biosphere (FloodList 2019a, b; Al Jazeera 2019) are evidenced in the increasing climate change triggered events. Some of these events are the unceasing rise in temperatures, droughts, floods, cyclones, storms and ice melts, and migration. Unfortunately, the compromise that follows the provision of energy for economic activities has not bridged the gap of energy insufficiency in many developing countries. About 50% of the population in 41 countries in sub-Saharan Africa (SSA) has no adequate access to energy; 650 million people are expected not to have access to power by 2030 (IEA 2017).

Apart from environmental and health issues caused by fossil fuels, the depletion of fossil fuels and the unabated price fluctuations is turning urgent attention to energy conservation. In this regard, several efforts have been advanced to check the environment and health issues associated with
energy generation and consumption. These include measures to reduce energy consumption, maximisation of the use of renewable energy (RE), use of hybrid renewable energy systems (HRES) (Rinaldi et al. 2021), digitalization, and decentralisation of energy systems (DCES), and the smart grid. In the same vein, the deployment of solar photovoltaic (PV) systems is increasing and due to the continuous decline of solar PV components prices. In addition, the utilisation of solar energy mitigates climate change consequences, promotes a decentralisation system, reduces the dependence on energy imports, and has extensive grid infrastructure.

### The need for alternative energy

The decision by the United Nations (UN) to cut down the global consumption of fossil fuel, to reduce the effect of CO₂ emissions was well-received globally (UN 2015). However, there is a need to develop alternative energy sources to replace fossil fuel; since energy is what powers socioeconomic growth. These alternatives are expected to be clean, reliable, adequate, and affordable energy. Sustainable energy transition will simply be fiction or a mirage without alternative energy to replace fossil fuel (Ebhota and Jen 2018). Subsequently, the contemporary questions surrounding energy are centered on how to harness RE resources; raise the efficiency of supply and end-use; reduce CO₂ emissions originating from energy generation and consumption; provide clean energy for all. This implies that much advancement has to be made to improve and facilitate RE deployment. Renewable energy technologies such as solar, biofuels, hydro, geothermal, tidal, and wind are currently receiving massive interest in terms of deployment, investment, and research and development. In addition, nuclear energy has also been described as reliable, safe, clean, compact, competitive, and practically inexhaustible (Eiden 2014). However, because of the perceived side effects, many countries are skeptical about the use of energy although nuclear has enormous energy required for electricity.

### Solar energy

Amongst the three most harnessed RE resources (solar, small hydropower, and wind), solar photovoltaic is the most deployed. This is mainly because of its widespread availability coupled with the continuous price decline of PV components, easy installation, and low maintenance cost. Solar energy is regional dependent and the annual direct solar irradiation in some regions exceeds 300 Watt per square meter (W/m²). A study observed that many of the countries that are likely to experience a rapid increase in urbanisation are in solar-rich regions, such as Singapore, Nigeria, Spain, Australia, India, and South Africa (WEC 2013). This gives solar PV systems the greatest potential for wider utilisation in SSA. Singapore is already exploiting the PV system, and has planned to raise solar power through a roadmap that adopts two scenarios—a “baseline” (BAS) scenario and an “accelerated” (ACC) scenario (Roadmap 2020). The targets of these scenarios are BAS—1 GWp and 2.5 GWp by 2030 and 2050, respectively; ACC—2.5 GWp and 5 GWp by 2030 and 2050, respectively. The success of this plan will save the yearly CO₂ emissions of about 1.6 million tonnes (Mt) and 3.4 Mt by 2030 and 2050, respectively. The realisation of the significance of the massive deployment of the different scales of solar PV systems in SSA will help to address the frequent blackouts and inadequate power supply considerably. At the same time, it would facilitate the building of a sustainable energy system in the end, which will reduce CO₂ emissions (Njoku and Omeke 2020).

Despite the successes recorded in solar efficiency, structure, and cost, the efficiency of multi-crystalline silicon photovoltaic (PV) cells is hovering around 10% to 17% (Kammen and Sunter). Recently, PV laboratory studies have reported efficiency of over 40%, using concentrated multi-junction cells (NREL 2016). Researches are ongoing to further improve the PV panel conversion performance and cost decline. Solar power is location depended, hence, this study provides PV potential and system information required for reliable and optimised solar PV systems at a location in Glenmore Crescent, Durban.

The goal of this study is to assess the solar PV Potential and performance of a 6-kWp system grid-connected for a household in site at Durban North, Durban, South Africa. The study is expected to provide information that will facilitate accurate PV system sizing and offer both economic and technical guides to installers and investors. Additionally, policymakers will find this study useful in forming the relevant framework to boost the provision of clean electricity. The objectives of this study include evaluation of the yearly average:

1. Global horizontal irradiation (GHI)
2. Direct normal irradiation (DNI)
3. Diffuse horizontal irradiation (DIF)
4. Global tilted irradiation (GTI)
5. Ambient temperature (TEMP)
6. Specific photovoltaic power output (PVOUT specific)
7. Total photovoltaic power output (PVOUT total)
8. Performance ratio (PR)

### Background of study

#### Solar resource basics and modeling solar radiation

Solar radiation is used to assess the potential power levels that can be generated from photovoltaic cells and is
necessary for determining cooling loads for buildings. Hence, accurate quantification of solar radiation is required for various PV system applications, such as agricultural and water resource planning, management, and the design of irrigation systems. Additionally, solar radiation is the most basic and reliable renewable and clean energy source in nature that can play an alternative role to fossil fuels. Therefore, the knowledge of solar radiation is essential for the optimal design and evaluation of solar energy applications, such as photovoltaic and solar-thermal systems. Solar radiation takes a reasonable time before it reaches the Earth’s surface, causing it to have various extra-terrestrial interactions with the atmosphere and surfaces of objects along its path. The amount of solar radiation per unit of horizontal area for a given locality is called, insolation, it originates from the sun, and depends mainly on the distance between the earth and sun, and solar zenith angle. Insolation can also be altered by the atmosphere, topography, and surface features, as it travels down the earth. At the earth’s surface, it forms three radiation components, as shown in Fig. 1—direct, diffuse, and reflected radiations—the direct radiation makes a direct line from the sun as it is intercepted by the earth unobstructed; the diffuse radiation is dispersed by atmospheric constituents, such as dust and clouds as it travels through them; and the reflected radiation hits on surface features along its path and gets reflected. The summation of these three radiation components is called global or total solar radiation.

Amongst these three components, direct radiation is the largest component, followed by diffuse radiation while the reflected radiation constitutes the least proportion, except for locations surrounded by highly reflective surfaces, such as snow-covered areas. The point locations or entire geographic area’s radiation can be estimated using solar radiation tools and this involves the following four steps (Rich et al. 1994; Cioban et al. 2013; Alamoud 2000):

1. The computation of an upward-looking hemispherical viewedash based on topography.
2. Estimation of direct radiation by overlaying the viewedash on a direct sun map.
3. Estimation of diffuse radiation by overlaying the viewedash on a diffuse sky map.

This process can be repeated for every location of interest to create an insolation map.

**Mathematical calculation of insolation**

The solar radiation analysis tools compute insolation throughout a landscape or for particular locations, center on techniques from the hemispherical view-shed algorithm created by Rich et al. (Rich et al. 1994; Fu and Rich 2002). The total radiation is computed for a specific location and is given as global radiation. The computation of direct, diffuse, and global insolation is replicated for every featured location on the topographic surface, creating insolation maps for the total geographical area.

**Direct Normal Irradiation/Irradiance (DNI)** is the element that deals with the photovoltaic concentration technology (concentrated photovoltaic, CPV) and thermal (concentrating solar power, CSP).

**Global Horizontal Irradiation/Irradiance (GHI)** is the summation of direct and diffuse radiation collected on a horizontal plane. GHI is used as the basis for climatic zones radiation comparison and is an essential parameter for computing radiation on a tilted plane.

**Global Tilted Irradiation/Irradiance (GTI)**, or total radiation collected on a surface with set tilt and azimuth angles, fixed or sun-tracking is the summation of the direct, scattered, and reflected radiation. It is occasionally affected by shadow and is used for PV applications.

**Global radiation calculation**

The estimated global radiation (Global\(_{tot}\)) is (ArcMap 2020):

\[
\text{Global}_{tot} = \text{Dir}_{tot} + \text{Dif}_{tot}
\]

where \(\text{Dir}_{tot}\) and \(\text{Dif}_{tot}\) are direct and diffuse radiation of all sun map and sky map sectors, respectively.

\[
\text{Dir}_{tot} = \sum \text{Dir}_{\theta,\alpha}
\]

\[
\text{Dir}_{\theta,\alpha} = S_{\text{Const}} \times \beta_{\text{ret}(\theta)} \times \text{SunDur}_{\theta,\alpha} \times \text{SunGap}_{\theta,\alpha} \times \cos(\text{AngIn}_{\theta,\alpha})
\]

where \(\text{Dir}_{\theta,\alpha}\) is the direct insolation from the sun map sector \((\text{Dir}_{\theta,\alpha})\) with a centroid at zenith angle \((\theta)\) and azimuth angle \((\alpha)\); \(S_{\text{Const}}\) is the solar constant, and 1367 W/m\(^2\) is usually
used in the analysis; \( \beta \) is the transmissivity of the atmosphere; \( m(\theta) \) is the relative optical path length; \( \text{SunDur}_{\theta,a} \) is the time duration represented by the sky sector; \( \text{SunGap}_{\theta,a} \) is the gap fraction for the sun map sector; \( \text{AngIn}_{\theta,a} \) is the angle of incidence between the centroid of the sky sector and the axis normal to the surface.

Relative optical length, \( m(\theta) \), is function of solar zenith angle (\( \theta \)) and elevation above sea level. For zenith angles less than 80°, relative optical length, \( m(\theta) \):

\[
m(\theta) = \exp(-0.000118 \cdot \text{Elev} - 1.638 \cdot 10^{-7} \cdot \text{Elev}^2) / \cos(\theta)
\]

(4)

Angle of incidence (\( \text{AngInSky}_{\theta,a} \)):

\[
\text{AngIn}_{\theta,a} = \cos(\text{Cos}(\theta) \cdot \cos(\text{Gz}) + \sin(\theta) \cdot \sin(\text{Gz}) \cdot \cos(\alpha - \text{Gz}_a))
\]

(5)

where \( \alpha \) is the surface azimuth angle, and \( G_z \) is the surface zenith angle.

**Computation of diffuse radiation**

The diffuse radiation at its centroid (\( D_g \)) is estimated, integrated over the time interval, and corrected by the gap fraction and angle of incidence utilizing this expression in (6):

\[
\text{Dif}_{\theta,a} = \text{R}_{\text{gib}} \cdot \text{P}_{\text{dif}} \cdot \text{Dur} \cdot \text{SkyGap}_{\theta,a} \cdot \text{Weight}_{\theta,a} \cdot \cos(\text{AngIn}_{\theta,a})
\]

(6)

where \( \text{R}_{\text{gib}} \) is the global normal radiation; \( \text{P}_{\text{dif}} \) is the proportion of the diffused global normal radiation flux (it is usually estimated 0.2 for very clear sky conditions and 0.7 for very cloudy sky conditions); \( \text{Dur} \) is the time interval for analysis; \( \text{SkyGap}_{\theta,a} \) is the gap fraction for the sky sector (proportion of visible sky); \( \text{Weight}_{\theta,a} \) is the proportion of diffuse radiation starting from a given sky sector relative to all sectors; \( \text{AngIn}_{\theta,a} \) is the angle of incidence between the centroid of the sky sector and the intercepting surface.

The global normal radiation (\( \text{R}_{\text{gib}} \)) can be computed by summing up the direct radiation from every sector, without correction for angle of incidence, then correcting the proportion of direct radiation, which equals 1 - \( \text{P}_{\text{dif}} \):

\[
\text{R}_{\text{gib}} = (S_{\text{Const}} \cdot \text{\( \sum \)}(p^{m(\theta)})) / (1 - \text{P}_{\text{dif}})
\]

(7)

\[
\text{Weight}_{\theta,a} = (\cos(\theta_2 - \cos(\theta_1)) / \text{Div}_{\text{azi}}
\]

(8)

where \( \theta_1 \) and \( \theta_2 \) are the bounding zenith angles of the sky sector; \( \text{Div}_{\text{azi}} \) is the number of azimuthal divisions in the sky map.

For the standard overcast sky model, \( \text{Weight}_{\theta,a} \) is computed as follows:

\[
\text{Weight}_{\theta,a} = (2 \cos(\theta_2) + \cos(2\theta_2 - 2 \cos(\theta_1 - \cos(2\theta_1)) / 4 \cdot \text{Div}_{\text{azi}}
\]

(9)

Total diffuse solar radiation for the location (\( \text{Dif}_{\text{tot}} \)) is computed as the sum of the diffused solar radiation (\( \text{Dif} \)) from all the sky map sectors:

\[
\text{Dif}_{\text{tot}} = \sum \text{Dif}_{\theta,a}
\]

(10)

**Solar PV system design and simulation applications**

Many reliable and innovative software applications have been developed to carry out solar PV assessment, system design, costing, energy generation prediction, and operation activities. Other uses are obtaining PV site location and meteorological information, assessing the site’s solar PV potential, and conducting system design, PV panel degradation assessment, and financial analysis. The impacts of the sun on a geographic area of a given period can be mapped and analyzed using solar radiation analysis tools that exploit two methods:

1. Calculation of insolation across an entire landscape, in a repeated manner for each location in the input topographic surface, using area solar radiation tool landscape.
2. Calculation of the amount of radiant energy for a specified location, using the point’s solar radiation tool.

In addition, they are used by solar installers for system design for stand-alone/off-grid, grid-connected, and hybrid systems for industrial plants, commercial, and residential buildings (Li 2021). Some of these applications and their uses are presented in Table 1.

**Economics of rooftop solar PV system**

The economic performance of the PV system depends on the following factors—the finance system, federal and local policies, utility rate, and level of technical potential available to the commercial PV rooftop. The evaluation of the financial benefits of a PV system requires an elaborate financial analysis to determine the levelised cost of energy (LCOE), return on investment (ROI), net present value (NPV), and internal rate of return (IRR). The IRR is the profit an investor gains in percentage form by investing in a solar PV system. The ROI offers a relatively simple view of how much money an investor will save over the total lifetime (usually 25 to 30 years) of a solar project.

There are two distinct merits of rooftop PV systems—power costs advantage and provision of clean electricity. The investment of rooftop is mostly through the operating expenses (OPEX) model or the capital expenditure (CAPEX) model. These are the commonest investment options. The operating expenses OPEX model involves the
provision of PV systems by the developers and sell the generated energy to the consumer. It requires legally binding; a long-term agreement between the consumer and the rooftop solar system provider and power purchase agreement (PPA) must be signed. In the case of the CAPEX model, the consumer owns the project and bears the capital expenses incurred during the installation of a rooftop system upfront. These expenses include the cost of equipment and other installation material, set up, labor, maintenance, upgrades, and operating the project. Excess residential power generated can be delivered to the grid. The OPEX model has the benefit of going solar without having to spend large upfront investments. Under the CAPEX model, the consumer takes ownership, quality, and safety responsibilities, unlike the OPEX model that is own and run by a third party. There are compromises in quality caused by saving costs by the third party in the CAPEX model. The CAPEX model is relatively cheaper than the OPEX model and hence, recommended for retail players and small and medium-scale enterprises.

**Levelised cost of energy**

Levelised cost of energy is the approximated revenue required to generate and run a generator over a given period of cost recovery is called LCOE. That is, the generated electricity from a known source is sold at a price to break even over the project lifetime (Huld et al. 2014). This energy cost evaluation method is based on OPEX and CAPEX estimates (Wolf 2015). Levelised cost of energy is used to measure and compare alternative means of energy generation and determine the viability of an energy project. Equation (14) is used to estimate LCOE (Huld et al. 2014):

\[
\text{LCOE} = \frac{1}{\sum_{t=1}^{n} \frac{\text{CAPEX,OPEN}_{t}}{(1+r)^t}} \sum_{t=1}^{n} \frac{\text{PVOUT}_{t}}{(1+r)^t} \tag{12}
\]

where \( I_t \) is the investment expenses in year \( t \); \( M_t \) is the maintenance and operations costs in year \( t \); \( F_t \) is the fuel costs in year \( t \) and \( t=0 \) zero for PV electricity; \( E_t \) is the electricity produced in the year \( t \); \( r \) is the discount rate; and \( n \) is the investment period in years.

Considering CAPEX as a primary input in the calculation of LCOE, utilizing the available most harmonised data set, Eq. (12) can be used (ESMAP 2020):

\[
\text{LCOE} = \frac{\sum_{t=1}^{n} I_t + M_t + F_t}{\sum_{t=1}^{n} E_t} \tag{11}
\]
emissions. The schematic diagram in Fig. 2 represents the flowchart of the methodology employed in this study.

**Location information and system description**

Detailed information of the site location is a requirement for an accurate solar PV potential estimation since the performance of the PV system depends on site-specific meteorological factors. These factors are wind speed, solar irradiance characteristics, and ambient temperature. Other determinants are installation site factors, which include dust, pollution level, latitude, orientation, and tree cover. The site is located in a residential area and a section of the site, as obtained from Google Map, is shown in Fig. 3.

For this study, a hypothetical household building was selected as a site, at a latitude of 29.800955°, the longitude of 31.0327245° in Glenmore Crescent, Durban North, South Africa. Other information on the selected site is presented in Table 2.

### Simulation of grid-connected PV system

The selection of the load profile, PV module, and installation types will be carried out using solar PV potential evaluator and design applications. Based on inputs optimisation considerations, the PV*SOL and Solargis software applications will be used to evaluate various parameters of a solar PV system, such as the daily, monthly, and yearly irradiations, terrain horizon, and day length, energy production, annual yield, and total system losses. In addition, a tabular comparative analysis of some critical solar system parameters overview will be presented. 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 other electrical accessories, as shown in Fig. 4.

### Simulation results and discussion

This section presents a detailed description of the load profile, configuration of the PV system, and the inputted parameters. It also includes simulation results presentation, analysis, and discussion of solar irradiations, energy production, annual yield, and total system losses.

### The description of the system

The installation type used in this study is a rooftop mount, meaning that the 6 kWp-installed capacity of the PV system was hypothetically mounted on a tilted roof of a residential building. The Azimuth and angle of tilt of the PV panels are harmonised such that the panels do not overlap or shade 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. 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. Details of other inputs used in this study are presented in Table 3.

The potential solar resource—solar irradiation

Solar insolation fuels the PV power system, hence, is the most significant project-specific meteorological parameter that defines or boosts solar electricity generation. Solar irradiation was used professionally to evaluate the energy yield of a PV system site at Glenmore Crescent, Durban North. The estimates of solar monthly and yearly variations of GHI, DNI, and DIF of the selected site, as obtained from Solargis Prospect, are depicted in Fig. 5a and b, respectively. Durban North has GHI relatively high in seven months—from January to March, and September to December and low for four months—April to August, as shown in Fig. 5a.

The highest irradiation of the site under consideration is in January; the results from Solargis Prospect and PV*SOL show 180 kWh/m² at 24 °C and 190 kWh/m² at 21 °C, respectively, as shown in Fig. 6a and b. The range of solar insolation received by the site throughout the year is from 95 to 190 kWh/m². The pattern of irradiance obtained, further strengthened the assertion that solar energy significantly depends on seasonal variation across the year.

Terrain horizon and day length

The length of a day is determined by the following factors—geographical latitude of the location, altitude of the sun, hour angle, and the sun declination angle. Figure 7a presents the horizon and sun path over a year in Durban North (the module horizon, terrain horizon, and active area with civil and solar time), which may have a shading effect on solar radiation. The change of day length and minimum zenith angle during a year are presented in Fig. 7b. The local day length (the time when the Sun is above the horizon) is shorter compared to the astronomical day length if obstructed by a higher terrain horizon.

Performance parameters

The sustenance of the ongoing development of the solar PV industry depends critically on the accurate PV system performance. The performance parameters are used to make comparisons of systems with different geographic locations, designs, and/or technology, and to allow operational problems detection. These parameters, which include performance ratio (PR), reference yield, final PV system yield, and Photovoltaics for utility-scale applications (PVUSA) rating, define the overall system performance concerning the solar resource, energy production, and total system losses effect.

Table 3 System information

| Load profile | 2-Person household with 2-children |
|--------------|-----------------------------------|
| Energy consumption (kWh) | 3500 |
| System size (kWP) | Installed capacity: 6 |
| Installation type | Roof mount |
| PV module type (%) | c-Si—crystalline silicon (mono), efficiency 18.9 |
| Geometry of PV modules (%) | Azimuth: 0; Tilt: 30 |
| Inverter type (%) | Inverter 95.9 (Euro efficiency) |
| Transformer type | No transformer |
| Snow and soiling losses at PV modules (%) | Monthly soiling losses up to 4.5; Monthly snow losses up to 0.0 |
| Cabling losses (%) | DC cabling 1; DC mismatch 0.8; AC cabling 0.2 |
| Albedo | 20 |
| System availability (%) | 97 |
Fig. 5  The estimates of a solar monthly and b yearly variations of GHI, DNI, and DIF of Durban North

Fig. 6  Monthly irradiation and temperature data at Durban North, South Africa obtained from a Solargis; and b PV*SOL

Fig. 7 a Path of the sun over a year in Surabaya; b Day length and solar zenith angle
One of the most significant variables for estimating the efficiency of a PV plant is PV performance ratio (PR).

The performance ratio is the ratio of the actual energy output and the possible theoretical energy output. It is mainly independent of the positioning of a PV plant and the incident solar irradiation on the PV plant. It is a measure of a PV system performance, taking into account meteorological factors, such as irradiation, climate changes, relative humidity (RH), and temperature. Hence, the PR can be used to compare PV plants supplying the grid at various locations all over the world.

The ratio between specific alternating current (AC) electricity output of a PV system and global tilted irradiation (GTI) obtained by the surface of a PV array, is termed as performance ratio (PR) (Quansah et al. 2017).

\[
PR = \frac{PV_{OUT\;specific}}{GTI}
\]

(13)

\[
PR = \frac{Y_f}{Y_r}
\]

(14)

\[
Y_f = \left( \frac{E_{out}}{P_o} \right)
\]

(15)

\[
Y_r = \left( \frac{H_i}{G_{i,ref}} \right)
\]

(16)

where \( PV_{OUT\;specific} \) is the specific photovoltaic power output (kWh/kWp), \( G_i \) is the sum of direct, diffuse, and ground-reflected irradiance incident upon an inclined surface parallel to the plane of the modules in the PV array, \( H_i \) is the in-plane irradiation kWh/m², \( E_{out} \) is the Energy output from PV system (AC), (kWh); \( P_o \) is the array power rating, AC, (kW).

The computation and report of PR are based on monthly or yearly output, although it can be calculated for smaller intervals, such as daily or weekly. This may be used to identify the occurrences of component failures. Because of losses due to PV module temperature, the values of PR in the winter are greater than in the summer, which usually falls within the range of 0.6 to 0.8. The maximum energy production is 1100 kWh in August, while the minimum is 810 kWh in February, as shown in Fig. 8. The reasons behind the high yield in August are the longest day of sunshine and low ambient temperature. The cloudy or rainy season is responsible for the low yield in February. Similarly, heavy electrical load, such as water geyser, and room heater connected to the system during winter accounts for the high-energy consumption (300 kWh) in July and August.

Effects of relative humidity, temperature, and wind speed

The power output of a PV system is significantly affected by the minimum and maximum ambient temperatures (Temp), wind speed (WS), and relative humidity (RH) (Park et al. 2013; Shrestha et al. 2019). The rise of cells temperature coupled with mismatch losses, dust accumulation, power-point errors, and shading, account for array capture losses (\( L_c \)), which is the difference between the reference \( (Y_R) \) yield an array yield \( (Y_F) \) (Marion et al. 2005; Shiva Kumar and Sudhakar 2015; Atsu et al. 2021). Where \( Y_F \) is also known as the final yield of the system. Mathematically, the array capture losses are computed using this expression:

\[
L_c = Y_R - Y_F
\]

(17)

High humidity, Temp, and WS affect the performance of the PV module adversely. The humidity condenses and creates a deposit on the PV panel at the night and this causes greater deflection of irradiance during the day. The curves of RH, temperature, and WS for the Durban North site showed a similar pattern, as presented in Fig. 10.

The testing and rating of solar panels are usually carried out at about 25 °C and are expected to perform optimally between 15 and 35 °C. However, during the summer, the temperature of solar panels in some areas may be as high as 65 °C (BostonSolar 2021). According to the meteorological information obtained from Solargis, the annual average
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The temperature of Durban North is 20.6 °C while the lowest (16.6 °C) and highest (24.3 °C) temperatures of Durban North were recorded in July and February, respectively. Further evaluation and analysis of the project-specific meteorological parameters, as presented in Fig. 11, shows that the relation between PR and RH; and PR and temperature are both inverses:

1. The highest PR corresponds to the lowest temperature value. This means that the PV system produces more energy at low temperatures. It implies that the solar PV system is more efficient at low temperatures.
2. The months (June and July) are of a very high PR, which corresponds to the months of a relatively low RH value. This means that the PV system produces more energy when humidity is low. Low humidity causes little limitation to electricity production by the solar PV system.

The efficiency of the PV module is highly affected by the sensitivity of the Si-based PV module to cell temperature. Consequently, there is a notable solar PV system efficiency loss in locations with long hot seasons, due to high temperatures. The negative effects of elevated temperatures on PV systems can be minimized in many ways. These include—leaving few millimeters between the panel and the roof to allow convectional airflow to cool the panels; use of light-colored materials to construct panels to reduce heat absorption; and keep components, such as inverters and combiners under a shaded area behind the array. The influence and relation of other solar PV parameters are presented in Fig. 12.

Where $G_{im}$ is the monthly sum of global irradiation (kWh/m²), $G_{id}$ is the daily sum of global irradiation (kWh/m²), $D_{id}$ is the daily sum of diffuse irradiation (kWh/m²) and $R_{id}$ is the daily sum of reflected irradiation (kWh/m²).

Fig. 9 Energy feed-in grid and energy consumption covered by PV and grid

Fig. 10 RH, Temp, and WS components of meteorological parameters
Durban North experiences temperatures between 16.6 and 24.3 °C, rainfall, spectacular thunderstorms, and high humidity that can make muggy days during summer, usually from October to March. These conditions hinder solar PV production performance and that is why the PR in these months is relatively low. In winter (June–August), the condition is different, as the temperature is between 0 and 20 °C and July is the sunniest month with an average temperature of 22 °C. The various weather conditions across the year are shown in Fig. 13a. The southern position in the hemisphere accounts for the times of sunrise and sunset in South Africa. Part of autumn (May) and winter months (June–August) have the longest days, while the summer months (December–February) have the shortest days (Worlddata.info 2021). The Durban average monthly hours of sunshine is represented in Fig. 13(b).

**Other PV performance determinants**

Many parameters, aside from the ones discussed above, are used to determine the potential of PV and the level of performance of a location and system, respectively. Some of these are the ratio of diffuse horizontal irradiation to global horizontal irradiation (D2G); the Fraction of solar irradiance reflected by surface, the ratio of upwelling to downwelling (GHI) radiative fluxes at the surface, known as surface albedo (ALB). Others are soiling losses and snow losses; the quantification of energy demand needed to cool a building, called cooling degree-days (CDD); and the quantification of energy demand needed to heat a building called heating degree-days (HDD). This study estimated values of these parameters are presented in Table 4.
Evaluation of soiling

The deposition of contaminants, such as dust, snow, dirt, moss, sand, and other particles on surfaces of the PV panels, causes higher absorption and reflection of sunlight. The growth of lichens and mosses and the accumulation of dirt along the frame of the panels can produce partial shadings on the base cells. The droppings from birds pose a serious problem because they cannot be removed by rainfalls. Amongst these contaminants, the dust of typical particle sizes of less than 10 mm in diameter though it depends on the location and environment, is the commonest. Dust is generated from different sources, such as pollution by wind, pedestrians, vehicular movements, and volcanic eruptions. This occurrence reduces solar irradiation, leading to lower energy conversion and yield losses of about 1% or more daily (Ilse et al. 2018); studies have reported that over 50% power reduction possibility by soiling (Sulaiman et al. 2014, Costa, Diniz, and Kazmerski 2018) and soiling effect depends on the nature of the contaminant. Soiling has the following negative effect on the economic revenues of PV installations—reduction in the converted energy by the PV system and increase in the cost of maintenance and operation. This creates further uncertainty on the assessment of PV system performance, prompting higher financial risk and charge of interest rates plant developers. Soiling causes an estimated loss of 4% on the world energy yield of PV and this account for about $2 \times 10^9$ USD loss annually (Smestad et al. 2020).

Table 4  PV performance determinants

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Yearly |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|--------|
| D2G   | 0.393 | 0.372 | 0.36 | 0.349 | 0.325 | 0.312 | 0.337 | 0.37 | 0.417 | 0.438 | 0.447 | 0.415 | 0.384 |
| CDD degree days | 179 | 175 | 172 | 172 | 106 | 69 | 37 | 29 | 42 | 44 | 66 | 94 | 143 | 1155 |
| HDD degree days | 0 | 0 | 0 | 0 | 3 | 19 | 32 | 20 | 11 | 1 | 0 | 0 | 87 |
| Soiling losses % | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 |
| Snow losses % | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
The effect of soiling may be ignored in the middle Europe that experiences medium rainy climates and in residential zones with less than 1%. However, it is important to consider soiling in rural areas with agricultural activities and industrial and railway line zones. The estimation of soiling of PV modules can be done with specialised sensors, a method described as a station-based measurements approach, and directly from the PV energy yield, described as a yield-based approach. Photovoltaic design and simulation software applications, such as PVsyst and Solargis Prospect, are also used to evaluate the effect of soiling on PV performance. The soiling loss (GL) is accounted for in terms of irradiance during simulation. In this case, irradiance losses are evaluated as (Zorrilla-Casanova et al. 2013):

$$GL(\%) = \left( \frac{G_{CC} - G_{DC}}{G_{CC}} \right) \times 100$$ (18)

where $G_{CC}$ is the clean reference solar cell irradiance value measured (W/m²); and $G_{DC}$ is the dirty reference solar cell irradiance value measured (W/m²), soiling loss (GL).

However, this can be quickly estimated as follow:

1. The region with a long dry season = 5%.
   - Plus 1–2% if the region experiences frequent dust deposition
   - Plus 1% if near a major vehicular traffic area

2. Region with year-round season = 2%.

In this study, an average soiling loss of 4.5% yearly was reported by Solargis Prospect and this amount was uniform in all the months, as presented in Table 4.

### Solar PV performance: energy conversion and system losses

The evaluation of the long-term average performance ratio (PR) is important and required for a start-up production of a PV system. The overview of the theoretical yearly specific estimate of solar electricity generation by a PV system, without the long-term aging and performance degradation of PV modules and other system components reflection, are presented in Table 5 and Fig. 8.

The estimation of the energy conversion and losses steps using Solargis PVplanner can be categorized into two components—losses numerically modeled by pvPlanner and losses that are assessed by the user. The integration of these components gives the theoretical losses due to energy conversion in the PV power system, as depicted in Fig. 14.

### Economic PV potential: investment consideration parameters

The cost of a PV system depends on on-site location, size and type of installation, type of PV cell technology, and quality of other components. One of the considerations that count in choosing the type of energy to be used is cost. Apart from the conscientious global effort to reduce the use of fossil, the commercial PV panel price decline is mainly responsible for the rapid increase in the deployment of solar PV systems. This section presents financial parameters that are used to establish the investment prospect of a PV system and these include LCOE, IRR, and ROI. The financial parameters inputs required for financial evaluation are presented in Table 6.

Amongst these, derived financial parameters, the simplified LCOE, which describes the cost of generating a unit of energy, is normally used to express the economic potential of solar PV. This is because LCOE connects CAPEX, OPEX, cost of the PV technology, discount rate, and PV plant lifetime. In this study, the calculated LCOE represents the solar PV economic potential by South Africa and the global weighted average CAPEX for a utility-scale PV system of 1,7671 USD/kWh and 1,020 USD/kWh (ESMAP 2020) The estimated IRR project, IRR equity, ROI, and LCOE based on South Africa, and global weighted average CAPEX for the 6-kWp PV system are shown in Fig. 15 shows.

### Table 5 System losses and performance ratio

| Energy conversion step | Energy output | Energy loss | Performance ratio |
|------------------------|--------------|------------|-------------------|
|                        | kWh/ kWp     | kWh/ kWp   | % Partial %        | Cum. %    |
| Global in-plane irradiation (input) | 1873         | –          | 100.0             | 100.0     |
| Global irradiation reduced by terrain shading | 1865         | –7         | 99.6              | 99.6      |
| Global irradiation reduced by reflectivity | 1817         | –48        | 97.4              | 97.1      |
| Conversion to DC in the modules | 1594         | –224       | 87.7              | 85.1      |
| Other DC losses | 1506         | –88        | 94.5              | 80.4      |
| Inverters (DC/AC conversion) | 1469         | –38        | 97.5              | 78.4      |
| Transformer and AC cabling losses | 1447         | –22        | 98.5              | 77.3      |
| Reduced availability | 1403         | –43        | 97.0              | 74.9      |
| Total system performance | 1403         | –469       | 25.1              | –         |

### Equation

$$GL(\%) = \left( \frac{G_{CC} - G_{DC}}{G_{CC}} \right) \times 100$$ (18)
In December 2020, the price of electricity of 0.145 USD/kWh for households was reported in South Africa while the global average price of electricity was put at 0.136 USD/kWh (GlobalPetrolPrices 2021). In Germany, the LCOE of a rooftop PV system is in the range of 0.053–0.12 USD/kWh, as reported in June 2021 (Kost et al. 2021). Relatively, LCOE of 0.1147 USD/kWh and ROI of 11% in a developing country, such as South Africa is very competitive and viable from a business sense.

Performance comparison

The summary of the technical performance simulation of the solar PV system obtained from the three PV software applications is reported in Table 7. The results obtained from software applications, PV*SOL, Solargis Prospect, and PVplanner, were similar. The outputs from Solargis Prospect and PVplanner were closer, while PV*SOL

![Table 6 Financial inputs](image)

**Table 6 Financial inputs**

| Description                                      | Value          |
|--------------------------------------------------|----------------|
| Price of electricity                             | 0.12 USD/kWh   |
| Tariff indexation rate (%)                       | 0.50           |
| **Annual operational costs**                     |                |
| Annual operational costs (USD)                   | 150            |
| Maintenance reserve account (USD/annually)       | 70.0           |
| Year of inverter replacement (years)             | 12.0           |
| OPEX (USD/annually)                              | 220.0          |
| OPEX inflation rate (%)                          | 2.00           |
| **PV system configuration**                      |                |
| Project’s years of operation (years)             | 25.0           |
| System availability 97.00%                       |                |
| PVOUT_total (year 0) (kWh)                       | 8,653.5        |
| Degradation first year (%)                       | 0.80           |
| Degradation next years (%)                       | 0.50           |

![Diagram: The theoretical losses due to energy conversion in the PV power system](image)
energy output deviates much more, compared to the other two. Solargis Prospect and PVplanner reported March as the month with the highest energy output while PV*SOL shows maximum energy output in August. The rise in temperature causes a decrease in solar PV output; hence, the output in March should be less, while the moderate temperature in August allows energy conversion from the solar PV system. This was observed in PV*SOL energy output only and the PR pattern outputs of both Solargis and PVplanner applications. The PR obtained from PV*SOL is significantly higher than Solargis software applications.

Table 7 Summary of results obtained from PV*SOL, and SolarGIS Prospect and PVplanner

| Parameter                              | PV*SOL  | SolarGIS-Prospect | SolarGIS-PVplanner |
|----------------------------------------|---------|-------------------|--------------------|
| **Meteorological parameter**           |         |                   |                    |
| Global horizontal irradiation (kWh/m²) | 1877    | 1659.3            | 1865               |
| Direct normal irradiation (kWh/m²)     | 1610.6  |                   |                    |
| Diffuse horizontal irradiation (kWh/m²)| 636.6   |                   |                    |
| Air temperature (°C)                   | 15.5    | 20.6              | 20.9               |
| **Performance parameter**              |         |                   |                    |
| Annual PV energy (kWh)                 | 10,583  | 8639              | 8419               |
| Spec. annual yield (kWh/kWP)           | 1763.88 | 1439.8            | 1403               |
| The month with max energy output       | August  | March             | March              |
| Average PR, (%)                        | 88.89   | 77.7              | 74.9               |
| Avoided CO₂ emissions (kg/year)        | 5662    |                   |                    |
| Solar fraction (%)                     | 42.5    |                   |                    |

**Conclusion**

The goal of this study is to assess the solar PV Potential and performance of a 6-kWP system grid-connected for a household in site at Durban North, Durban, South Africa. The study is expected to provide information that will facilitate accurate PV system sizing and offer both economic and technical guides to installers and investors. Additionally, policymakers will find this study useful in forming the relevant framework to boost the provision of clean electricity.

Solar PV systems stand out amongst the RE technologies currently being exploited due to their resources distribution, level of advancement, and the degree of resource available for use. Photovoltaic potential and system assessment is an optimisation and a site-based study, which offers both economic and technically relevant information to PV system investors, designers, and installers. Hence, the target of this study is an assessment of solar PV resources and the performance of a grid-connected 6-kWP PV system for household use in a site at Durban North, Durban, South Africa. This will provide accurate and precise data that will facilitate reliable PV design, system installation, and greater deployment of PV systems for clean electricity. Additionally, this study is useful to policymakers in formulating policies and RE roadmap to improve and increase the provision of clean electricity.

A hypothesised monocrystalline solar PV system was used to predict the economic and technical performance parameters of a 6-kWP installed capacity grid-connected rooftop solar PV system to supply electricity to a household. The study was performed using PV*SOL, SolarGIS-Prospect, and SolarGIS-pVPlanner software applications. The parameters evaluated include the yearly average of GHI, DNI, DIF, GTI, TEMP, PVOU T specific, PVOU T total, and PR. Other parameters are energy yield assessment, energy consumption, and electricity feed-in-grid. Variations were
observed in the predicted values in the reports obtained from the different software applications. Some of the parameters that were different were seen are annual energy production, specific annual energy yield, PR, and energy yield. These variations were attributed to the difference in model equations and source of climate data amongst the simulation software applications. However, the absence of checked irradiance data and PV power output restraints the proof of the results. The study presents some valuable perceptions into the rooftop PV system to meet the normal household’s energy needs, irrespective of the noted shortcomings. The highlights as obtained from the simulation results are as follows:

1. The reported annual energy yield of 1403 kWh/kWp, shows that the monocrystalline PV module rooftop grid-connected system installations in Durban North of South Africa is a technically viable green energy alternative for residential areas, government buildings, business centers, etc.
2. Depending on the available rooftop area, the PV energy production performance is good with the scope of capacity scale up above 6 kWp in the Durban North region.
3. The annual energy production of 8419 kWh was reported and about 86% of this was fed into the grid.
4. The solar PV system PR of 74.9% obtained is satisfactory for installation and commissioning.
5. By using the proposed PV system, an estimated 43% reduction of the annual energy requirement from the electrical grid was obtained.
6. Comparatively, PV*SOL exhibits easy, fast, and most reliable trends as a simulation tool for the solar PV system.
7. The proposed grid-connected rooftop PV system in Durban North is feasible as the results show technical viability, with the benefits of clean energy provision, CO2 emission reduction, and energy savings.
8. Others are economic performance parameters – levelised cost of energy (LCOE) 0.1147 USD/kWh, internal rate of return (IRR) 17,671 USD/kWh, and return on investment (ROI) 11%.

The results show that the proposed solar PV system under the current conditions is both economically and technically viable for household electrification in Durban North, South Africa.

Future study

An empirical study, as an extension of this research, is required to validate the simulation results. This will include the collection of data through direct measurement of irradiance and the power output of a 6-kWp installed capacity of a monocrystalline silicon rooftop PV system in a sited at Durban North, South Africa.

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Declarations

Conflict of interest

The authors declare that there is no conflict of interest.

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