Analysis of Residential Rooftop PV Systems under South African Climatic Conditions: A Case Study of eMalahleni

A. ABAYOMI, AGHA F. NNACHI
Department of Electrical Engineering
Tshwane University of Technology, eMalahleni
SOUTH AFRICA

Abstract: The South African energy market is strained owing to load shedding, ageing power station and the ever-increasing tariffs. The alternative energy source is renewable energy. This research assesses the technical and financial feasibility of a 5.4 kWp grid-connected rooftop solar PV system for small residential units in eMalahleni (Witbank).. Utilizing PVSOL, SolarGIS, and PVSYST simulation tools, performance is evaluated under high-solar-resource conditions with global horizontal irradiation ranging from 1,900 to 2,000 kWh/m². Results indicate high performance with yields of 1,800 to 1,861 kWh/kWp, performance ratio values of 73.8 to 76.9%, and a capacity factor of approximately 18%, matching global standards. Over 83% of the power generated is fed into the grid, making domestic consumption decrease by over 40%. SolarGIS provides conservative results, PVSYST provides optimistic results, while PVSOL provides a balanced estimate. From an economic perspective, the system is 35% cost-effective with a payback period of 6-8 years, making rooftop solar a feasible option for eMalahleni households in the long run.

Key-Words: - Tariffs; Valuation; Energy Yield; Optimization; Modeling

Received: May 29, 2025. Revised: September 16, 2025. Accepted: December 21, 2025. Published: May 22, 2026.

1 Introduction

Solar energy is at the top of the most prevalent renewable energy technologies; it is clean compared to conventional power generation, [1]. Photovoltaic (PV) systems are the most widely used type of renewable power source because they are modular, scalable, and economically viable, [2]. In the case of South Africa, the national power grid is no longer reliable; this is attributed to increased cases of load-shedding and increased costs of electricity. This has attracted many people to install PV power systems in their homes. In South Africa, over 80% of the electricity generated from the power grid is obtained from coal sources, and this is from the thermal stations owned by Eskom. Most of these power stations are located in the Mpumalanga province, [3]. Most people believe that eMalahleni (Witbank) is the power capital of the nation because it has large coal-fired power stations such as Duvha, Kendal, and Kusile power stations. Despite the power stations' closeness to eMalahleni, the town suffers from power shedding, increased costs of electricity, and reduced power reliability, [4]. Globally, rooftop solar PV has been recognized as a decentralized technology that can improve the energy resilience of households, lower carbon emissions, and offer economic benefits by means of self-consumption, [4]. South Africa, boasting high solar irradiance of 4.5-6.5 kWh/m²/day, is particularly suited to the implementation of solar PV technology as part of its energy transformation strategy. Recent changes in policy, such as the exemption of small-scale embedded generation projects (up to 100 MW) from the licensing process, have further promoted the development of decentralized solar solutions, [5].

On-grid or grid-connected PV systems have received more attention than their off-grid or stand-alone counterparts, mainly due to their enhanced ability to supplement household loads and inject the surplus electricity produced into the national grid, [6]. In urban and peri-urban areas like eMalahleni, rooftop PV integration presents an opportunity for households not only for partial energy independence but also for contributing to grid stability, especially during daytime peak demand. The impact of such systems will be to ease pressure on the coal-based power lineup of the national power utility, as well as lower GH gas emissions, [7]. In relation to being viable, solar power availability and climatic conditions within the area that has to support a solar power setup will be beneficial. This will include having adequate global solar Horizontal Irradiance (GHI) and attaining a temperature of 21°C. This is important as it will include locations that annually receive approximately 1900 to 2000 kWh of such solar irradiance. This makes eMalahleni similar to locations elsewhere around the world that receive high solar irradiance, [8].

The performance characteristics of PV systems are highly dependent on the meteorological parameters related to the irradiance of the sun, ambient temperature, humidity, and wind speed. For an optimum design of the PV systems, a detailed analysis is required on the parameters related to the site, [9]. The standard metrics used for performance evaluation include annual energy yield, performance ratio, and capacity factor, [10]. Many studies across the globe have employed such metrics to assess PV feasibility in residential and utility-scale installations. For example, the authors in [11], showed that optimal PV system sizing is predominantly site-specific, while the authors in [12], indicated that small-scale grid-connected systems could reliably meet up to 90% of residential energy needs in favourable climates. From the context of the case study, several studies have begun to investigate PV system deployment under varying climatic and demand conditions. However, much of the work carried out has not concentrated on household-scale, grid-connected rooftop PV systems in regions dominated by energy from coal, like in the case of eMalahleni. Considering the high-energy environment in which the case study region is couched, it is important to have localized work carried out to ensure a test of economic feasibility. Hence, in this present work, it is intended to use simulation to determine the performance of a grid-connected rooftop PV system in small-scale households in eMalahleni, touching on implications of technical performance indicators to a bigger extent regarding economic feasibility. As shown in Table 1, the study site is characterized by high solar irradiance and moderate average temperatures, making it suitable for rooftop PV deployment. Table 2 details the system configuration, including module type, orientation, and load profile used in the simulation model.

Table 1: Site information

Site Name	eMalahleni (Witbank), Mpumalanga, South Africa
Coordinates	25.87° S, 29.23° E
Annual global irradiation	1950 kWh/m² (Global Horizontal Irradiance)
Annual air temperature at 2 m	21.0 °C (average)

Source: created by the authors

Table 2: System description

PV power rating	5.4 kW (rooftop system)
Type of modules	Mono-crystalline
Efficiency	18%
Mounting system	Fixed mounting, true north orientation
Azimuth/inclination	0° (north-facing) / 25° tilt
Load profile	4-person household with daily load ~14 kWh
System availability	95%

Source: created by the authors

These mono-crystalline PV modules have a temperature coefficient of -0.41%/°C, which impacts the performance directly during summer seasons when the temperature goes high.

Initially, in South Africa, there was no supportive legislation for embedded generation, but the new reforms include net billing, as well as simplified small-scale embedded generation schemes for registration. These changes in legislation have led to an increase in the adoption rate of rooftop solar PV in residences due to the potential profitability associated with it.

2 System Description

In the proposed power generation system, a 5.4kWp grid-connected rooftop PV power generation system is designed for a small domestic setup for the eMalahleni area in South Africa. Mono-crystalline PV modules have been opted for in the proposed design of the power generation system since these modules are more efficient and best suited for the high irradiation rate found in South African climatic conditions. Moreover, the proposed power generation system is designed in a fixed tilt mounting arrangement with a size suitable for the average daily power consumption requirement of a small family. In the proposed power generation unit, the solar arrays are used for extracting or harnessing the energy from the sun in the form of DC power after converting the captured sun's light into electrical energy. The Maximum Power Point Tracker devices in the proposed power generation unit enhance the power generated from the PV modules. Finally, in the proposed power generation unit, the grid-connected Inverter device converts the DC power into Alternating Current (AC) for domestic consumption and for a safe grid power supply. Various other additional devices in the proposed power generation unit include Mounting Structures, Wiring Components, and grid-connecting safe devices such as DC/AC Breakers and Fuses that are designed as per the South African Utility requirements. A schematic representation of the grid-connected Rooftop PV power generation unit has also been displayed in the following figure: Figure 1.

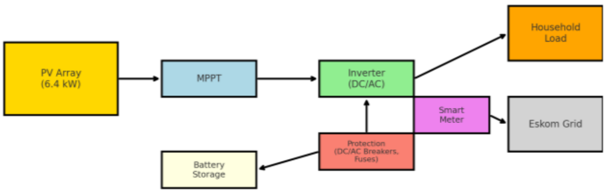

Fig. 1: Layout of a small-scale grid-tied rooftop PV system

Source: created by the authors

The above figure represents the schematic representation of a grid-connected rooftop solar PV system for a small-scale residential setup in the case study. The system consists of solar PV panels, MPPT, an inverter, protection components, a residential connection, a grid interface, battery storage for reliability, and a smart meter for monitoring and tariff optimization. In the context of a case study, where the reliability of electricity supply is often threatened by load shedding, the combination of a battery energy storage system (BESS) with a grid-connected rooftop solar PV system is highly advantageous. The BESS enables the storage of surplus solar electricity produced during the day, which can then be drawn during the peak hours of the evening or during power outages, [13]. This enhances energy security for households while reducing dependency on the utility grid during high-tariff periods. Also, storage supports grid stability by minimizing power fluctuations caused by intermittent solar generation, [14]. The inclusion of a smart meter adds further value by enabling real-time monitoring and control of energy consumption and generation. With the TOU tariffing system implemented by the utility company, smart meters enable households to make optimal decisions on the use, storage, or export of energy, [15]. At midday, when the production of solar energy is at its highest and the cost of energy is low, the extra power generated can be stored in the battery or fed back into the grid. After that, at the peak hours of the evening, when the price of power is high, the home would be able to use the saved power instead of drawing it from the grid. This would be a great improvement in the cost efficiency, load shedding, and utilization of PV power. , [16].

3 Description of Modelled System

3.1 Simulation of a Grid-Connected PV System using PV-SOL

In this research, the simulation of a grid-connected rooftop PV system for a small-scale 5.4 kWp household rooftop PV system in eMalahleni, South Africa, was performed using the PVSOL software developed by Valentin Software. *PV*SOL is widely used for the planning, sizing, and performance estimation of photovoltaic systems. It allows designers to model the installation environment, determine optimal system configurations, and evaluate the expected energy yield, [17]. The software incorporates a climate database that provides location-specific meteorological parameters, such as solar irradiation, temperature, and wind speed. The software permits manual input of location coordinates when more specific site details are required. For the study site, climate data were obtained from the built-in *PV*SOL database to reflect realistic operating conditions.

The simulation process begins with defining the project environment, including the site location, household load profile, and roof characteristics such as azimuth and inclination. The PV technology is then selected from a database of available modules, where mono-crystalline modules were chosen for their higher efficiency in South African conditions. The system is dimensioned by specifying either the target output capacity or the number of modules, with the software automatically calculating the gross PV area required. Spacing between modules is also factored in to reduce shading effects and allow for adequate maintenance access. Subsequently, inverter configurations are selected to ensure maximum power transfer between the DC output of the PV modules and the AC supply fed into the household and the utility grid. A maximum power point tracker (MPPT) is included within the inverter model to optimize real-time power output. After the system parameters have been determined, the PVSOL engine engine carries out an hourly simulation based on the meteorological data. The simulation provides essential performance data, such as the annual irradiation on the horizontal and tilted surfaces, the annual PV energy production in kilowatt-hours, and the performance ratio of the system. These results enable a thorough evaluation of the technical viability and efficiency of the PV system for the eMalahleni case study. .

Below is a conceptual flowchart of the PV-SOL simulation methodology:

Start → Define Project (New Project Setup)
→ Input Site Location (Witbank Climate Data)
→ Specify Roof Orientation & Tilt (Azimuth & Inclination)
→ Select PV Module Technology (Mono-Crystalline)
→ Enter Desired System Capacity / Number of Modules
→ Configure Inverter & MPPT Settings
→ System Sizing & Layout Verification
→ Run Simulation (Hourly Yield Calculation)
→ Obtain Outputs (Irradiation, PV Yield, Performance Ratio)
→ Generate Project Report → End

3.2 Simulation of a Grid-Connected PV System using SolarGIS

Besides PVSOL, the SolarGIS PV Planner was used to simulate and assess the performance of the grid-connected rooftop PV system in the case study. SolarGIS is a web-based computer program that combines high-resolution geographical and climatic data for the design and optimization of PV systems. It is a map-based tool that enables the user to enter the exact coordinates of the location, which is very useful for location-specific assessments. The simulation process begins by accessing the SolarGIS online platform where the search function is used to identify the desired site, [18]. For this study, the exact coordinates of the case study were entered to ensure local conditions were accurately represented. Once the site was confirmed, the system capacity was defined according to the household requirements, and the corresponding PV module type was selected from the available database. Further technical details, like inverter efficiency, approximate DC to AC conversion losses, mount type, and angle of tilt, were defined later, taking into consideration feasible system parameters. The software is set to automatically consider climatic factors like solar radiation, horizon shading, sun path, and ambient temperature for the respective locality. The above parameters enable SolarGIS to produce a comprehensive system performance analysis.

The information generated from this software consists of the approximate yearly photovoltaic potential, electrical energy production, and energy losses in different system operation stages. In addition, performance ratio, average irradiation levels in each location, as well as the effect of meteorological conditions, are calculated in a yearly period. The information generated is an exact indication of how well a rooftop solar system in eMalahleni performs in its climatic conditions and serves as a means to compare with information generated from software programs such as PV-SOL.

3.3 Simulation of a Grid-Connected PV System using PVSYST

The third simulation platform employed in this study is PVSYST**,** a software package originally developed at the University of Geneva for the analysis and design of PV systems. PVSYST is widely recognized in both academia and industry as one of the most reliable tools for assessing PV system performance under site-specific conditions, [19]. Unlike web-based platforms, PVSYST provides a more comprehensive and customizable environment where system designers can simulate different configurations, optimize sizing, and evaluate losses in considerable detail. The simulation starts with the definition of the project location in terms of geographical coordinates. Meteorological information such as solar irradiance, ambient temperature, and wind speed is provided using the PVSYST database. This is necessary because of the variability of the climate in the region. The system configuration is where the type of solar module is selected. It is chosen as mono-crystalline because of its compatibility with PVSOL and SolarGIS models. The configuration of the solar system is where the number of modules in series and parallel is defined, as well as the type of inverter and the maximum power point tracking settings.

PVSYST automatically verifies whether the selected configuration is compatible with the electrical constraints of the inverter and highlights any mismatches.

A significant advantage of PVSYST lies in its detailed loss diagram or “loss table”, which provides a breakdown of system inefficiencies at each stage of power conversion. Losses can arise from a variety of factors, including optical losses due to shading and reflection, thermal losses caused by elevated module temperatures, wiring and cabling resistances, inverter conversion losses, and system unavailability. The software allows users to adjust assumptions about these parameters, thereby providing a transparent framework for sensitivity analysis. This makes it possible to identify design weaknesses and optimize the system for higher efficiency and reliability. PVSYST also allows the simulation outputs to be displayed in hourly, daily, or monthly time steps, depending on the intended application. For household-level PV systems, hourly data are particularly valuable because they allow the identification of mismatches between production and consumption patterns, [20]. In this study, the hourly output was used to compare production with a typical small household load profile in eMalahleni. This provides insights into self-consumption potential, the role of battery storage, and the magnitude of electricity exported to the utility grid. Monthly and annual summaries are also generated to provide long-term performance indicators.

The outcome of the simulation using PVSYST includes important parameters such as the annual energy production, efficiency, and performance ratio of the system. Additionally, the software allows the measurement of the percentage of losses that can be attributed to the various system components, which is important information for system optimization and cost-benefit analysis. In the South African scenario, where high electricity costs and power outages are prevalent, the information generated from the PVSYST simulation is important for the evaluation of the economic and technical viability of small-scale grid-connected solar PV systems. The inclusion of PVSYST simulation in this study, together with PVSOL and SolarGIS simulation tools, ensures the development of a comprehensive methodological framework. Although PVSOL and SolarGIS allow fast and easy simulations, PVSYST allows a more detailed analysis of the performance of solar PV systems. The approach ensures that the final analysis of the case study is robust and relevant to the context.

3.4 Loss Modelling Assumptions in the Three Simulation Tools

The major loss factors influencing PV yield predictions were harmonized as closely as possible across the tools, including:

- PV module mismatch losses: 1.5–2.0%.
- Soiling/dust losses: 2–4%
- Inverter conversion losses: 3–4%.
- Temperature-related losses controlled by the module temperature coefficient (−0.40 to −0.45%/°C)

Variations in how each simulation tool internally models degradation, availability, and thermal behavior contribute to the performance ratio differences observed in the results. This clarification ensures transparency in the comparative assessment.

4. Simulation Result and Discussion

4.1 Solar Irradiation Resource Evaluation

Figure 2 above shows the monthly average of global horizontal solar irradiation as well as the average temperature in eMalahleni, South Africa. The graph indicates a bimodal distribution of solar irradiation with a higher amount during the summer period (October to March) and a lower amount during the winter period (May to July). The amount of solar irradiation increases due to longer daylight hours and a smaller amount of solar radiation scattered by the atmosphere; thus, the maximum amount of solar irradiation recorded is almost 190 kWh/m² for January and December. The minimum amount recorded is almost 110-120 kWh/m² for June and July.

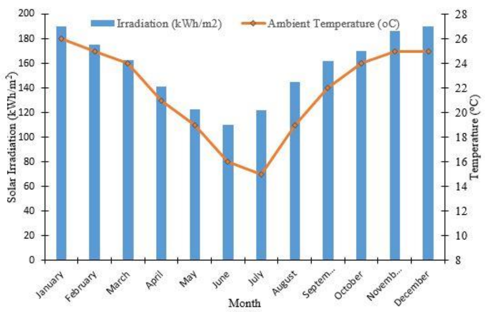

Fig. 2. Monthly average global horizontal solar irradiation and temperature *PV*-Sol

Source: created by the authors

Ambient temperature exhibits an inverse relationship with irradiation during the winter months. It decreases from an average of 26 °C in January to approximately 14–15 °C in June and July, then increases toward the end of the year. In the winter, when the temperature outside is lower and the amount of sunlight hitting the ground is less, photovoltaic (PV) systems may not produce as much energy overall. However, the cooler operating conditions also cut down on thermal and resistive losses in the PV modules, which helps to make up for the fact that there is less sunlight available. Because of this, when looking at how well PV works, you need to look at how temperature and solar irradiance work together instead of separately. In January, February, and December, when the irradiance is high, the open-circuit voltage drops because charge carriers recombine more easily in the semiconductor material. This can lower the efficiency of the module. As a result, PV electricity generation in South Africa does not always rise in direct proportion to increased solar irradiance, illustrating the intricate relationship between thermal influences and solar resource availability. This is why the amount of electricity that PV systems in South Africa produce doesn't always go up in a straight line with the amount of sunlight they get. In contrast, during winter, even though irradiation is lower, the cooler operating environment allows the system to maintain relatively stable efficiency. This balance between irradiance availability and temperature-driven efficiency underpins the importance of performance ratio (PR) analysis in system simulation studies.

There are big effects on rooftop PV installation in eMalahleni. First, the variation in irradiation from 110 to 190 kWh/m² per month indicates that the area receives a lot of solar power throughout the year.

Therefore, eMalahleni is a great place for small solar panels to be set up and connected to the grid.

Second, the fact that the seasons change in a predictable manner means that the solar panels can be designed to get the most out of the power generated during the months when the sun is not shining as much.

They can also be designed to have a battery to help during this period.. Third, the effects of ambient temperature show how important it is to choose module technologies with good temperature coefficients, like mono-crystalline silicon with passivated emitter rear contact (PERC) cells, to reduce efficiency losses in the summer. Another important thing to think about is the effects of climate on eMalahleni's semi-urban and industrial environment, such as humidity and dust, which are not shown in the graph but are still important. The high levels of particles from coal-fired power plants and mining in the area could make soiling losses on PV modules worse. This further supports the idea of adding regular maintenance schedules to the operation of PV systems so that they work well all year long.

The seasonal patterns of irradiation and temperature in eMalahleni show that grid-connected rooftop PV systems can work for homes and small businesses. The data show that winter months only slightly limit energy yield, but the overall annual resource potential is more than enough to make sure the system works reliably. With the right design strategies, like the best module orientation, smart inverter integration, and hybridization with storage, PV systems in this area can produce a lot of energy while also helping to ease the grid supply problems and load-shedding issues that are common in South Africa.

SolarGIS data shows the monthly average global horizontal solar irradiation (GHI) and the temperature around eMalahleni, South Africa, as shown in Figure 3. The seasonality is obvious, with the maximum irradiation values during the austral summer months of December to January (values around 180 to 185 kWh/m²) and the minimum during June with 110 kWh/m². This correlates with the orbit of the sun in the Southern Hemisphere, when it and its duration are longest during summers and shortest during winter. The ambient temperature varies seasonally from 15°C in July to 26°C in January. The close association between thermal and radiation cycles implies that solar energy availability and atmospherics are interrelated. Moderate winter minima are significant as they indicate that although solar irradiation is low, it is well above 0°C. This increases thermal losses in solar panels in high latitudes. The solar irradiation in March averages 205 kWh/m² during this period. The influence of seasonality is again obvious, with high solar irradiations during September to November, with averages of 190 to 195 kWh/m². The temperature varies from 15°C in July to 16°C in March.

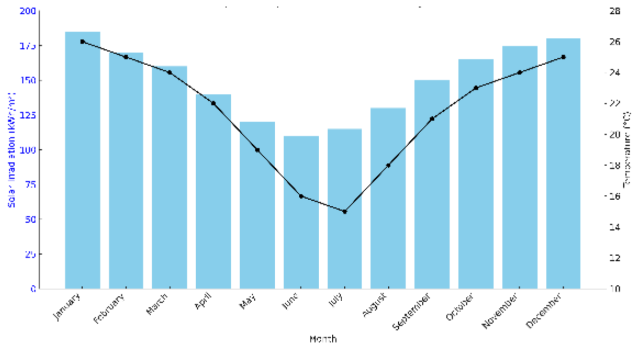

Fig. 3. Monthly average global horizontal solar irradiation and ambient temperature by SolarGIS

Source: created by the authors

From an energy systems perspective, the high summer irradiation coincides with peak cooling demand, thereby supporting the integration of solar PV for demand-side management. Equally, the reduced winter irradiation implies the necessity for hybridization or storage strategies to ensure supply reliability. The relatively stable annual distribution further confirms eMalahleni's suitability for large-scale solar deployment, with a favourable balance between irradiation potential and operating temperature range, minimizing PV derating due to thermal stress.

The simulation results for eMalahleni, South Africa, derived from PVSYST, show that both global horizontal irradiation (GHI) and ambient temperature change a lot from season to season, as shown in Figure 4. The monthly average GHI is highest in December and January, when it is over 180 kWh/m². It is lowest in June, when it is about 112 kWh/m². This seasonal change is a direct result of the solar declination cycle in the Southern Hemisphere. In the summer, longer days and higher solar elevations increase insolation, while in the winter, they decrease it. The ambient temperature has a seasonal pattern that is similar but a little behind. In the summer, it peaks at around 26–27 °C, and in the winter, it drops to around 16 °C. PVSYST gives slightly higher thermal readings than SolarGIS. This is probably because it uses different methods to combine meteorological data. When the sun is at its highest, the temperature rises, which affects how well photovoltaic (PV) systems work because module efficiency goes down as the temperature rises. However, Witbank's mild winter lows help keep thermal cycling to a minimum, which is good for the long-term reliability of PV systems.

From a resource adequacy perspective, the relatively high annual average GHI (>150 kWh/m² per month) underscores the region's suitability for utility-scale solar energy projects. The synchronous rise of cooling demand and solar resource availability during summer further enhances the value proposition for PV integration into the regional grid. However, the reduced winter irradiation highlights the necessity for complementary strategies such as energy storage, hybridization with wind or dispatchable generation, or demand-side management to ensure year-round supply stability. The PVSYST dataset confirms Witbank's strong solar resource base, with favourable irradiation and manageable thermal conditions. These findings strengthen the case for large-scale solar deployment in Mpumalanga Province, particularly for grid-supportive PV projects aimed at reducing dependence on fossil-based generation.

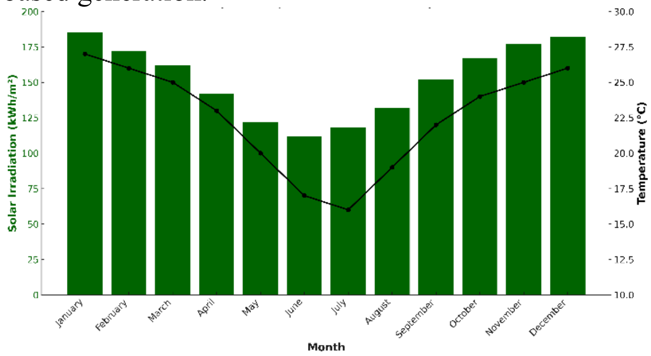

Fig. 4. Monthly average global horizontal solar irradiation and ambient temperature by PVSyst
Source: created by the authors

Three separate simulation platforms, PV-SOL, SolarGIS, and PVSYST, were used to compare the monthly average global horizontal irradiation (GHI) and ambient temperature for the case study. Even though each tool uses different weather data and modeling methods, their outputs show consistent seasonal patterns, though with small differences in numbers that have big effects on system design and performance estimates. GHI is highest in the southern summer months (December to January), when it reaches values over 175–185 kWh/m². It is lowest in June, when it is around 110–120 kWh/m². This seasonal change is similar to the solar declination cycle that happens in the Southern Hemisphere.

- SolarGIS gives fairly conservative estimates, with yearly averages that are very close to long-term satellite-based climatological records.
- PVSYST tends to predict slightly higher irradiation levels, especially in the spring and summer. This could be because it combines data from ground-based weather stations with Meteonorm adjustments.
- The results of PV-SOL are usually somewhere between those of SolarGIS and PVSYST, which suggests that they are a mix of data from local weather stations and global radiation maps.

The practical implication is that PVSYST yields a marginally higher energy yield prediction during system simulations, while SolarGIS presents a more risk-averse resource baseline. For feasibility studies, it is therefore advisable to benchmark at least two datasets to quantify uncertainty margins. Ambient temperature profiles across the three datasets exhibit seasonal patterns consistent with Witbank's subtropical highland climate, with summer averages

DOI: 10.37394/23201.2026.25.10

between 25–27 °C and winter minima between 15–17 °C.

- **SolarGIS** reports slightly lower annual average temperatures, remaining conservative in its upper ranges (~25–26 °C).
- **PVSYST** consistently shows higher readings, with summer peaks up to 27 °C. This upward bias is critical for PV performance modelling, as module operating temperatures strongly affect efficiency.
- **PV-SOL** values align closely with measured regional climate norms, thus often serving as a reasonable middle ground.

While differences of 1–2 °C may seem marginal, they translate into measurable deviations in predicted energy yield due to the temperature coefficient of PV modules (typically –0.4 to –0.5 %/°C). The comparative analysis shows that PVSYST's higher irradiation but elevated temperature values partly offset one another in yield projections, while SolarGIS provides conservative estimates that reduce overestimation risk. PV*SOL's results are usually in the middle, which makes it a good tool for comparing how well things are working. Cross-referencing all three datasets makes it easier to guess how financially stable and how much electricity will cost (LCOE). All three datasets agree that Witbank has a lot of potential as a solar hub. The average annual GHI levels are well over 1,800 kWh/m², and the weather is good for putting up PV systems. However, systematic differences in magnitude highlight the importance of dataset triangulation in the development of feasibility studies or investment-grade resource assessments. In real life, SolarGIS gives a safe starting point, PVSYST gives a positive view, and PV-SOL gives a fair view. The project design is better when you use the best parts of each. This makes sure that it is both technically and financially sound. The 5.4 kWp grid-connected rooftop PV system in eMalahleni shows that PVSOL, SolarGIS, and PVSYST all have similar but different performance characteristics. Annual PV energy output is highest in PVSYST (10,050 kWh), followed closely by *PV*SOL (9,850 kWh), while SolarGIS provides the lowest estimate (9,720 kWh) as presented in Table 3 (Appendix). This spread highlights the effect of dataset choice, with PVSYST generally optimistic due to higher irradiation assumptions, while SolarGIS maintains a more conservative outlook.

The specific annual yield presented in Figure 5 follows a similar trend, ranging from 1,800 kWh/kWp (SolarGIS) to 1,861 kWh/kWp (PVSYST). Such differences, though moderate, can impact energy yield projections over a project's lifetime, influencing bankability assessments and LCOE calculations. The performance ratio (PR), a critical parameter representing the overall efficiency of the system after accounting for system losses, shows notable variation across the platforms. PVSYST records the highest PR at 76.9%, suggesting more efficient conversion under its modelled conditions, while SolarGIS yields the lowest PR at 74.6%, and PV-SOL lies in between at 75.3%. These variations stem from differences in loss modelling (temperature losses, inverter efficiency, and system availability) applied in each simulation tool. From a technical perspective, the relatively high PR values (>74%) across all platforms confirm the suitability of eMalahleni's solar resource base for residential PV deployment. The dataset triangulation underscores the importance of the differences in the performance ratio, where the PVSYST overrated the solar irradiation inputs, while SolarGIS provides a more conservative reference point for risk-averse planning. PV-SOL reaches a balance point between the two, offering a functional operational tool, especially when such a tool is calibrated on the basis of data recorded at a given PV system location. This study clearly indicates that while all three tools confirm the validity of the location as suitable for the implementation of rooftop PV systems, care must be taken in the consideration of the estimates for PR to ensure the accuracy of system size calculation, cost prediction, and reliability.

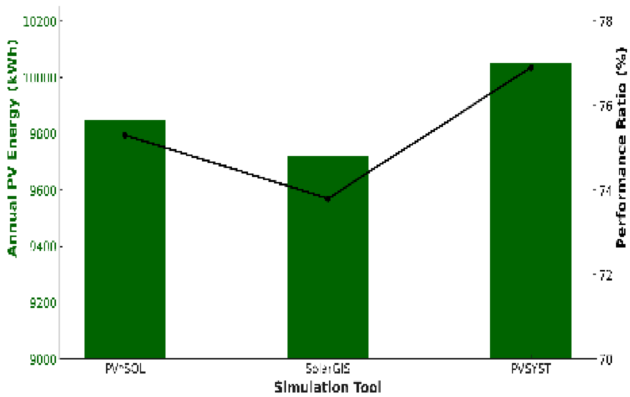

Fig. 5. Comparison of annual energy yield and PR values

Source: created by the authors

4.2 Comparative Analysis of Simulation Tools

The systematic differences between the tools can be attributed to internal assumptions governing loss mechanisms. SolarGIS applies conservative availability and thermal loss factors, resulting in lower annual yields. HOMER Pro assumes slightly optimistic inverter and soiling losses, producing the highest performance ratio estimates. PVSyst uses a detailed loss-diagram architecture, explicitly accounting for electrical mismatch, irradiance angle-of-incidence losses, and spectral effects. These methodological differences explain the yield spread of 1,800–1,861 kWh/kWp across the three simulations.

5 Economic Assessment

To complement the technical performance analysis, a simplified economic evaluation was carried out using local tariff structures and installed system costs. Based on current rooftop PV market prices in South Africa, the total installed cost of a 5.4 kWp system is estimated at ZAR 90,000–110,000. The annual energy savings achievable from reduced grid consumption and net-metered export revenues amount to ZAR 13,000–15,500 per year. This results in a payback period of approximately 6–8 years. Over a 25-year operational lifetime, the system provides 35–40% total energy cost savings, thereby confirming strong financial viability for small-scale residential PV adoption in eMalahleni.

6 Conclusion

In this paper, the technical performance of a 5.4 kWp grid-connected rooftop PV system in eMalahleni, South Africa, is evaluated using PV-SOL, SolarGIS, and PVSYST. Results show how sensitive performance predictions can be due to climate databases and/or differences in model structures, and hence the importance of multi-dataset comparisons during system design. Measured irradiance and output data could not be accessed for checking, but the simulations show a good overview of the rooftop PV performance in the area. The simulated annual energy production ranged from 1,800 to 1,861 kWh/kWp, while the respective performance ratio ranged from 74.6% to 76.9%, which is within benchmark international standards for very well-optimized grid-connected systems. This proves that the region is of high solar resource potential. Of the electricity that was produced, over 83% was fed into the grid. Thus, this reduced the dependence of households on the grid by approximately 40%. This demonstrates small-scale PV facilitating the energy independence of people. It was a comparative analysis to show that each one of these tools has its peculiar characteristics. For instance, SolarGIS conservative lower bounds are good for risk-averse planning, while PVSYST projects higher yields but is sensitive to temperature; likewise, PV-SOL provides balanced operational benchmarks with practical design flexibility. The convergence of strong yield potential with consistently high PR values implies competitive LCOE performance and enhances the bankability of household-scale PV investments. The results shows that the installation of rooftop PV panels in the eMalahleni area is viable from the technical and economic stances. Wider dissemination with the necessary policy and funding mechanisms in place may contribute significantly to improved energy resilience in urban areas and the low-carbon transition in the energy sector.

References

[1] Soudagar, M.E.M., Ramesh, S., Khan, T.Y., Almakayeel, N., Ramesh, R., Ghazali, N.N.N., Cuce, E. and Shelare, S., 2024. An overview of the existing and future state of the art advancement of hybrid energy systems based on PV-solar and wind. *International Journal of Low-Carbon Technologies*, 19, pp.207-216. https://doi.org/10.1093/ijlct/ctad123

[2] Ahmed, S., Ali, A., Ansari, J.A., Qadir, S.A. and Kumar, L., 2025. A Comprehensive Review of Solar Photovoltaic Systems: Scope, Technologies, Applications, Progress, Challenges and Recommendations. IEEE Access, vol.13, pp. 69723-69750. https://doi.org/10.1109/ACCESS.2025.3558539

[3] Adebiyi, A.A., Lazarus, I.J., Saha, A.K. and Ojo, E.E., 2019. Performance analysis of 8 kW Grid-tied solar photovoltaic power plant in Durban South Africa. *International Journal of*

Mechanical Engineering and Technology, 10(4), pp.140-153. https://www.doi.org/10.34218/IJARET.10.4.2019.017.

[4] Price, R., 2022. Resources on the just energy transition in South Africa, Helpdesk Report 1134. Institute of Development Studies pp. 1-30. https://doi.org/10.19088/K4D.2022.098 .

[5] Van Schalkwyk, L. and Scholtz, M., 2024. Incentives and drivers for private embedded generation through solar photovoltaic systems in South Africa. F*rontiers in Environmental Economics*, 3, pp.1-18. https://doi.org/10.3389/frevc.2024.1463241

[6] Hamid, A.K., Mbungu, N.T., Elnady, A., Bansal, R.C., Ismail, A.A. and AlShabi, M.A., 2023. A systematic review of grid-connected photovoltaic and photovoltaic/thermal systems: Benefits, challenges and mitigation. *Energy & Environment*, 34(7), pp.2775-2814. https://doi.org/10.1177/0958305X221117617

[7] Hanto, J., Schroth, A., Krawielicki, L., Oei, P.Y. and Burton, J., 2022. South Africa's energy transition–unraveling its political economy. *Energy for Sustainable Development*, 69, pp.164-178. https://doi.org/10.1016/j.esd.2022.06.006

[8] Ogundimu, E.O. and Richards, C.G., 2025. Modelling and Simulation a Solar Farm Energy-Based Smart Grid for Tshwane University of Technology (Emalahleni Campus), South Africa: Feasibility and Analysis Studies. *WSEAS Transactions on Power Systems*, 20, pp.29-41. https://doi.org/10.37394/232016.2025.20.3

[9] Iqbal, S., Khan, S.N., Sajid, M., Khan, J., Ayaz, Y. and Waqas, A., 2023. Impact and performance efficiency analysis of grid-tied solar photovoltaic system based on installation site environmental factors. *Energy & Environment*, 34(7), pp.2343-2363. https://doi.org/10.1177/0958305X221106618

[10] Jamil, I., Lucheng, H., Habib, S., Aurangzeb, M., Ali, A. and Ahmed, E.M., 2022. Performance ratio analysis based on energy production for large-scale solar plant. *IEEE Access*, 10, pp.5715-5735. https://doi.org/10.1109/ACCESS.2022.3141755

[11] Chintapalli, N., Sharma, M.K. and Bhattacharya, J., 2020. Linking spectral, thermal and weather effects to predict location-specific deviation from the rated power of a PV panel. *Solar Energy*, 208, pp.115-123. https://doi.org/10.1016/j.solener.2020.07.080

[12] Syed, M.M. and Morrison, G.M., 2021. A rapid review on community connected microgrids. *Sustainability*, 13(12), 6753, pp.6753. https://doi.org/10.3390/su13126753

[13] Kurdi, Y., Alkhatatbeh, B.J. and Asadi, S., 2023. The influence of electricity transaction models on the optimal design of PV and PV-BESS systems. *Solar Energy*, 259, pp.437-451. https://doi.org/10.1016/j.solener.2023.05.037

[14] Islam, M.M., Yu, T., Giannoccaro, G., Mi, Y., La Scala, M., Rajabi, M.N. and Wang, J., 2024. Improving reliability and stability of the power systems: A comprehensive review on the role of energy storage systems to enhance flexibility. *IEEE Access*, vol. 12, pp. 152738-152765. https://doi.org/10.1109/ACCESS.2024.3476959

[15] Normasari, N.M.E., Yuniarto, H.A., Gunawan, I.C., Silalahi, S.F., Deendarlianto, Aditya, I.A., Simaremare, A.A. and Haryadi, F.N., 2025. Dynamic pricing strategy with Time-of-Use (TOU) scheme in electricity pricing for household consumers in Indonesia–A systematic literature review. *Energy Strategy Reviews*, 60, 101802, pp.1-13. https://doi.org/10.1016/j.esr.2025.101802

[16] Adebiyi, A.A. and Moloi, K., 2024. Renewable energy source utilization progress in South Africa: a review. *Energies*, 17(14), 3487, pp.1-23. https://doi.org/10.3390/en17143487

[17] Kazem, H.A., Chaichan, M.T., Al-Waeli, A.H. and Gholami, A., 2022. A systematic review of solar photovoltaic energy systems design modelling, algorithms, and software. Energy Sources, Part A: *Recovery, Utilization, and Environmental Effects*, 44(3), pp.6709-6736. https://doi.org/10.1080/15567036.2022.2100517

[18] Cenky, M., Bendik, J., Janiga, P. and Lazarenko, I., 2024. Urban-Scale Rooftop Photovoltaic Potential Estimation Using Open-Source Software and Public GIS Datasets. *Smart Cities*, 7(6), pp.3962-3982. https://doi.org/10.3390/smartcities7060153

[19] Mishra, P.R., Rathore, S. and Jain, V., 2024. PVSyst enabled real time evaluation of grid connected solar photovoltaic system. *International Journal of Information Technology*, 16, pp.745-752. https://doi.org/10.1007/s41870-023-01677-x

[20] Govindarajan, L., Batcha, M.F.M., Abdullah, M.K. and Taweekun, J., 2025. Analysing the Performance of Large-Scale Rooftop Solar PV System Using Heliscope, PVsyst and PV* SOL Photovoltaic Simulation Software: As a Renewable Energy Strategy. *Journal of Advanced Research in Applied Sciences and Engineering Technology*, 52(1), pp.192-208. https://doi.org/10.37934/araset.52.1.192208

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors made equal and substantial contributions to this research, participating in all stages, from defining the research context to the conclusion.

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Sources of Funding

The authors did not receive any funding for this study.

APPENDIX

Table 3: Performance parameters for a 5.4 kWp household rooftop PV system in eMalahleni

Performance parameter	PV-SOL	SolarGIS	PVSYST
Annual PV energy (kWh)	9,850	9,720	10,050
Specific annual yield (kWh/kWp)	1,824	1,800	1,861
Own energy consumption (kWh)	1,420	1,420	1,420
Energy feed-in to grid (kWh)	8,430	8,300	8,630
Own power consumption (%)	14.4%	14.6%	14.1%
Total household energy consumption (kWh)	3,500	3,500	3,500
Covered by PV (kWh)	1,420	1,420	1,420
Covered by grid (kWh)	2,080	2,080	2,080
Performance Ratio (PR) (%)	**75.3**	**74.6**	**76.9**

Source: created by the authors