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Research Article

Energy losses in crystalline silicon rooftop photovoltaic systems in selected site locations in Sub-Saharan Africa

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Abstract. This study systematically evaluates Phototovoltaic (PV) system energy losses and performance quality across selected locations in sub-Saharan African (SSA). Utilising a computational model for a hypothetical 10 kWp crystalline silicon (c-Si) PV system, the research categorises energy losses into irradiance (kWh/m²) and electricity production (kWh/kWp). Key contributors to irradiance losses include angular reflectivity, dirt, dust, and soiling, while inverter and radiation conversion, spectral correction, transformer and cabling, and mismatch are identified as main sources of PV system energy losses. Tilt and orientation impact the transformation of Global Horizontal Irradiance (GHI) into Global Tilted Irradiance (GTI), with the highest gain in Pretoria (215.4 kWh/m²) and the least in Kinshasa (3.6 kWh/m²). The study notes the highest PV system energy loss in Pretoria (346.2 kWh/kWp) and the least in Kinshasa (267.4 kWh/kWp). Despite variations in energy loss sources, the cumulative degradation rate is reported as 12.8% for all locations over a 25-year lifespan. The annual average performance ratio (PR) and capacity factor (CF) range from 77.4%/19.7% in Pretoria to 77.4%/15.6% in Kinshasa. Ambient conditions, including wind speed, relative humidity, precipitation, and temperature, are identified as key factors influencing solar irradiance and PV system losses. The study suggests preventive measures such as optimal system design, the use of bypass diodes, and high-quality PV panels.

Keywords: Photovoltaic systems; Crystalline silicon; Photovoltaic energy losses; PV panel degradation; Inverter loss

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1. Introduction

Solar photovoltaic (PV) systems have had a significant societal impact since their introduction. One of the key societal impacts of PV is its role in the renewable energy transition. Photovoltaic technology plays a crucial part in the transition from fossil fuels to renewable energy sources. They offer clean, sustainable, and abundant sources of electricity, reducing dependence on fossil fuels, and mitigating climate change. This transition helps to reduce greenhouse gas (GHG) emissions and air pollution, improve public health and the environment (Bunda *et al.*, 2023; Rengma, Yadav, & Kishor, 2023). Photovoltaics facilitate greater access to clean electricity in remote and underserved areas where traditional grid infrastructure is lacking or prohibitively expensive. Solar-powered systems enable communities and individuals to meet their basic energy needs, such as lighting, communication, and refrigeration; improving living conditions and enabling economic opportunities. The widespread deployment of PV has led to the creation of numerous jobs in the manufacturing, installation, operation, and maintenance of PV systems. This has contributed to the growth of the renewable energy industry, fostering employment opportunities, and economic development. Photovoltaics empower individuals, businesses, and communities to generate their electricity, reducing reliance on centralized power systems. This energy independence enhances resilience, particularly during natural disasters or grid disruptions, and provides a sense of control over energy consumption and costs.

Another significance of PV is the provision of energy independence through reduced energy costs. As the cost of photovoltaic technologies has decreased over the years, solar power has become more economically competitive with traditional energy sources. Photovoltaics offer long-term energy cost savings for consumers, especially when combined with energy storage systems to utilize solar power during non-sunny periods. The development and deployment of PV have stimulated technological advancements in solar cell efficiency, energy storage, and grid integration. These innovations have not only improved the performance and reliability of solar systems but have also influenced advancements in other sectors, such as electric vehicles and smart grid technologies (Gianfranco *et al.*, 2022; Kasti, 2017; Mathijsen, 2021). Photovoltaics have raised public awareness about renewable energy and sustainability. They have provided educational opportunities for individuals to learn about solar energy, climate change, and energy conservation. This increased awareness has fostered a broader understanding of the importance of renewable energy in achieving a sustainable future.

The Paris Agreement, which was adopted in 2015, aims to strengthen the global response to climate change (Trenberth, 2015). One of the key goals of the agreement is to limit global warming to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C

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(Howarth & Viner, 2022; Palutikof *et al.*, 2023). The 1.5 °C target recognises that a half-degree increase can have significant impacts on ecosystems, human livelihoods, and vulnerable communities. This target is based on scientific assessments and recommendations from the Inter-governmental Panel on Climate Change (IPCC). To limit global warming to 1.5 °C, it is necessary to decarbonise multiple sectors, including transportation and heating. In this context, PV will play a significant role in the process by supplying renewable electricity to power electric vehicles, domestic appliances, and heating pumps. By coupling PV with energy storage technologies, we can ensure a continuous supply of clean energy, enabling the electrification of various sectors and reducing reliance on fossil fuels.

Photovoltaic power generation is virtually carbon-free, and it does not emit GHG during operation, making it a clean energy source. By transitioning to PV and other renewable energy sources, we can replace fossil fuel-based power plants and reduce emissions associated with electricity production, which is a major contributor to global warming (Ebhota & Jen, 2020). Scaling up the deployment of PV systems contributes to the overall increase in renewable energy capacity. Asa PV technology becomes more efficient and cost-effective, it becomes easier to deploy PV panels on rooftops, solar farms, and other suitable locations (Williams S. Ebhota & Pavel Y. Tabakov, 2022; Williams S. Ebhota & Pavel Y Tabakov, 2022). This scalable nature of PV enables rapid expansion of renewable energy generation, which is crucial for achieving the 1.5 °C target.

Although, PV technology has seen significant advancements and has become a major player in the renewable energy sector, also, it has certain limitations. Some of the key limitations of PV technology include (Dawoud, Lin, & Okba, 2018; Seedahmed *et al.*, 2022; Vaziri Rad, Kasaeian, Niu, Zhang, & Mahian, 2023) - intermittency and variability; land and space requirements; energy storage and grid integration; efficiency and performance; manufacturing and environmental impacts; and cost and affordability. Solar PV systems are subjected to intermittency and variability because they rely on sunlight to generate electricity. Their power output fluctuates depending on weather conditions, such as cloud cover and the time of day. This intermittency can pose challenges for grid integration and requires careful management and coordination with other energy sources or energy storage systems to ensure a stable and reliable power supply.

The most widely used material in solar cell manufacturing is c-Si due to its relatively high-efficiency rates of about 20-25%. However, several factors promote energy losses in the PV systems, which affect the overall performance and power output. Therefore, this study aims to evaluate the energy losses in crystalline silicon rooftop PV systems in selected site locations in SSA. It includes the identification and comprehensive analysis of some key PV power generation limiting factors based on computational modelling. Some of the research questions that form the core of the study's objectives to be addressed are: What is the global horizontal irradiance (GHI) and global tilted irradiation (GTI) of the chosen locations? What is the effective GTI and total percentage loss of each of the locations? What are the key factors accounting for energy losses in PV systems? What is the percentage contribution of each loss mechanism to the overall system losses? What is the Sensitivity analysis of key parameters influencing the losses? What are the measures to prevent or reduce the impact of these losses? What is the annual Cumulative degradation of c-Si PV cells at the different site locations? What is the annual capacitor factor of c-Si PV cells at the different site locations? What is the total system performance technical availability and losses due to snow?

The paper systematically addresses its objectives across six sections, beginning with Section 1. Section 2 (literature review) delves into energy requirements, consumption challenges, and the necessity of renewable energy (RE) technologies, such as PV systems. It discusses sources of energy losses in PV systems and their effects. Section 3 (method) details the methodology, including steps for deploying computational modelling. Section 4 concentrates on discussing and analysing the results. Sections 5 and 6 respectively outline measures to reduce energy losses in PV systems and conclude the study.

2. Literature review

Electricity consumption in the business and residential sectors is on a rapid upward trajectory due to growing population, industrialisation, and urbanisation. These developments come with higher demand for electronic appliances as business and personal equipment, at time solar PV technology is evolving. However, RE market growth, as a source of clean electricity, is unable to adequately support the needed energy due to several factors, which include low PCE, initial high cost of system installation capital and systems' energy losses. In the case of solar energy, the commercially available PV panels are of polycrystalline and monocrystalline silicon and they have PCE range of 20-25% only. What happens to the 75-80% of the energy received? Two-third of the energy delivered by the sun is not only lost, it is counterproductive to the energy generation, as it heats up the system. Notwithstanding, the global PV technology market is increasing because of its overwhelming benefits as an alternative to fossil fuel. These merits include system design, installation, and maintenance simplicity, abundance of solar resources, low maintenance and operation costs, and low CO_2 emissions.

Presently, coal and natural gas stand as the primary sources of electricity generation to meet the needed electricity for socioeconomic development. However, forecasts suggest that RE sources will contribute to nearly 50% of the world's total electricity generation by 2050. Among these sources, solar PV technology has emerged as the fastest-growing energy technology globally. This is owing to its utilisation of the sun, the most abundant RE resource available, along with its relatively low maintenance costs and competitive pricing compared to other RE technologies. Additionally, solar PV systems can be implemented at varying scales, from small to large. Notably, from 2012 to 2017, the demand for household electricity experienced its most significant surge in Asia, with an average annual growth of 3.7% (Anang, Syd Nur Azman, Muda, Dagang, & Daud, 2021). Projections indicate a substantial increase in residential building electricity usage, expected to double within 32 years, soaring from 22 quadrillion BTU in 2018 to 50 quadrillion BTU in 2050 (EIA, 2019a).

In contrast to large-scale PV plants, small-scale grid-connected rooftop PV systems offer assessments of solar potential in urban areas without utilizing land and reduce transmission and distribution costs. Consequently, the installation of these systems is escalating, and research in this field is expanding. The focus in this realm has shifted towards quality and performance research due to the enormous potential of small rooftop PV systems. Several studies (Heesen, Herbort, & Rumpler, 2019; Omar & Mahmoud, 2018) have investigated the performance of rooftop PV systems across various locations and conditions. Research in Germany examined the performance of rooftop PV systems in 13 states from 2012 to 2018. Similarly, in Abu Dhabi, four different buildings with grid-connected rooftop PV systems using two types of PV modules, poly-crystalline (p-c-Si) and mono-crystalline (m-c-Si) were analysed. Furthermore, in Morocco, the performance of 2 kWp p-c-Si, m-c-Si, and amorphous PV modules was scrutinised using real data collected over five years, comparing it with simulated data. Python was employed for simulations to predict power production for a week, and the root mean square errors for all three types of PV modules were compared (Ameur, Berrada, Loudiyi, & Aggour, 2020).

Despite PV efficiency improvements over the years, the efficiency rates are still at about 20-25% for commercial PV panels (NREL, 2022), prompting room for improvement. Higher efficiencies would allow for more electricity generation from a given area of PV panels, reducing the land or roof space required. Over the years, a substantial cost of PV panels decline has been witnessed, but the cost of upfront installation is still high. This creates a barrier to widespread adoption, especially in developing countries, and for low-income households. Additionally, the costs associated with PV system components, such as inverters and mounting structures, which contribute to the overall economics of PV installations are relatively high. Amid these limitations, PV technology continue to evolve, and ongoing research and development efforts aim to address these challenges.

Improvements in understanding, efficiency, energy storage, grid integration, and manufacturing processes can further enhance the capabilities and cost-effectiveness of PV systems. Breakthroughs in this context will make them more viable options for clean energy generation in the future. These challenges of energy losses need to be understood and resolved to facilitate greater clean energy delivery, improved output, reduced CO_2 emissions, running and payback costs. The PV system’s performance is affected by energy losses and this makes the net energy production to be between 20% and 25% PCE. Many studies have proposed solutions, such as static and dynamic reconfiguration and Maximum Power Point Tracking (MPPT) methods.

2.1. Sources of loss in PV sysyems

There are technical issues in PV systems that manifest in the forms of PV system losses including power loss in PV panels, which account for about 26% of the power generated (Bruce, 2023). The losses are attributed to ambient, meteorological, and climatic conditions of the site location and the system's limitations. The accuracy of a PV system in the delivery of power according to its designed capacity, depends on the holistic consideration of several variables. Some common technical issues are inverter losses, panel degradation, shading issues, dirt, dust and soiling, wiring and connection problems, monitoring system issues, lightning and surge protection, inadequate maintenance, and PV module thermal loss due to heating (Khalid *et al.*, 2023; Maghami *et al.*, 2016; Salamah *et al.*, 2022).

Energy loss in terms of GHI and GTI - Energy loss in terms of GHI refers to the reduction in the amount of solar energy received at a horizontal surface due to various factors and is measured in kWh/m². In the same way, energy loss in GTI refers to the reduction in the amount of solar energy received by a tilted surface, such as a solar panel or array, compared to the total solar radiation available in the absence of any tilt. Several factors are responsible for the energy losses in the context of GHI and GTI and these include atmospheric absorption and scattering, seasonal variations, pollution and aerosols, latitude, cloud cover, air mass, and daytime variation. In addition to the factors that contribute to GTI loss is tilt angle and orientation. The angle at which a solar panel is tilted and its orientation relative to the sun significantly impact the amount of solar radiation it receives. The optimal tilt angle and orientation depend on the geographical location and the specific application.

Angular reflectivity - Angular reflectivity, also known as the angular response or angular sensitivity, refers to how the performance of a PV system is affected by the angle at which sunlight strikes the PV modules. The PCE of PV modules is not constant across all incident angles of sunlight. Instead, it varies based on the angle of incidence, for example, the angle between the incoming sunlight and normal to the PV module surface. The angular reflectivity of a PV system is mainly influenced by two factors - angle of incidence (AOI) and surface properties.

2.2. Other PV issues

Shading is a significant concern for PV systems because even a small amount of shading on one panel can greatly affect the output of the entire system (Brecl, Bokalič, & Topič, 2021). Trees, buildings, or other obstructions that cast shadows on the panels can cause a decrease in power production. If shading issues are persistent, repositioning the panels or using bypass diodes can help mitigate the problem. Faulty wiring or loose connections leads to significant power losses or system failures. Poorly connected or damaged cables, connectors, or junction boxes can cause voltage drops and overheating. Regular inspection and maintenance of the wiring and connections are crucial to ensure proper performance (Osmani, Haddad, Lemenand, Castanier, & Ramadan, 2020). Lightning strikes and power surges can damage the PV system's components, including the panels, inverter, and electrical circuits. Installing appropriate surge protection devices and earthing systems can help mitigate the risk of damage from electrical surges. Like any other electrical system, PV systems require regular maintenance to ensure optimal performance. Neglecting maintenance tasks such as cleaning the panels, inspecting wiring, and checking system components leads to reduced efficiency and potential issues.

2.3. Photovoltaic system losses

2.3.1. Spectral correction in PV

Spectral correction in PV refers to the process of adjusting or compensating for the differences in the incident solar spectrum and the response characteristics of a PV device (Polo *et al.*, 2020). The solar spectrum consists of electromagnetic radiation with a wide range of wavelengths, and different wavelengths of light have varying effects on the performance of a PV cell. Photovoltaic cells are typically designed to operate optimally under standard testing conditions (STC), which define a reference spectrum with a specific distribution of light intensity across different wavelengths. However, the actual solar spectrum can deviate from the reference spectrum due to various factors, such as atmospheric conditions, location, and time of day. Spectral correction techniques aim to account for these deviations and adjust the electrical output of the PV device accordingly. This correction can be important because the response of a PV cell varies with the incident wavelength of light. Some PV technologies, such as c-Si-based cells, have a higher sensitivity to certain wavelengths, while others, like thin-film technologies, may have a broader spectral response. To perform spectral correction, researchers and engineers utilize various methods such as:

i. External filters (Winck, da Fonseca, Gasparin, & Krenzinger, 2020) - These are additional optical filters placed in front of the PV cell to modify the incoming light spectrum. Filters can be designed to enhance or suppress specific wavelengths, thus matching the incident spectrum to the cell's optimal response.

ii. Multijunction cells - Multijunction solar cells consist of multiple sub-cells with different bandgaps that are tuned to capture a broader range of the solar spectrum. By combining sub-cells with different sensitivities to different wavelengths, multijunction cells can achieve higher overall efficiency (Meusel, Adelhelm, Dimroth, Bett, & Warta, 2002).

iii. Spectral splitting (Han, Tu, & Sun, 2021; Xia *et al.*, 2023; Zhang *et al.*, 2021) - This technique involves splitting the incoming sunlight into different spectral ranges and directing each range to a separate PV cell or material optimized for that particular wavelength range. It allows for more efficient utilization of the solar spectrum across different PV materials.

iv. Spectral conversion (Winck *et al.,* 2020) - Some PV technologies, such as luminescent solar concentrators, employ materials that can convert specific wavelengths of light into a range that matches the optimum response of the PV cell. This conversion process helps enhance the overall efficiency by utilizing a broader spectrum of light.

Spectral correction techniques are important in maximising the energy conversion efficiency of PV devices and ensuring their performance under varying spectral conditions. By accounting for the spectral distribution of light, PV systems can generate more accurate and reliable energy output predictions, leading to improved overall system performance.

2.3.2. Solar PV Panel Degradation

Photovoltaic panel degradation is a phenomenon that affects the performance and lifespan of solar panels over time. It is caused by various factors, such as ageing, corrosion, delamination, light-induced degradation (LID), potential-induced degradation (PID), outdoor exposure, and environmental conditions. Solar Panel degradation reduces the efficiency and output of solar panels year after year. The rate of panel degradation depends on the quality and type of the solar panels, as well as the installation and maintenance practices. Generally, crystalline silicon (c-Si) PV panels degrade at a rate of ≤1% yearly. During service, PV modules are exposed to different kinds of external stresses that affect their performance and lifetime over time. This occurrence is a phenomenon, caused by certain factors (Dunlop & Halton, 2006; Oliveira, Diniz Cardoso, Viana, & Lins, 2018), categorised into three:

External stresses - The c-Si PV panels are designed to work outdoors for not less than 25 years. This process exposes PV panels to different sets of external stressors, such as ultraviolet (UV) irradiation, elevated temperature and humidity cycles, hail, dust, sand, snow, wind loads, and salt rain. This exposure degrades the PV module's protective materials and facilitates failure of different modes and the eventual low PCE and shortened service life.

Internal stresses – PV module is a product of multilayer systems of several different components, joined adhesively to each other to form many different materials interfaces. Normally, a panel comprises glass, cell, encapsulant, and back sheet arranged and bonded together in this pattern to form four interfaces; glass/encapsulant/cell/encapsulant/back sheet, as shown in Fig 1. These interfaces are potential weak points for leaks due to morphology, additives, and compatibility differences of the materials. This scenario causes internal stress, leading to leakage of currents and PV panel degradation.

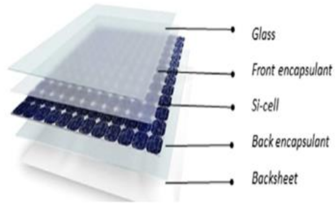

Fig 1. Exploded view of a PV panel (Omazic *et al.*, 2019)

Climatic influence - The climate has a significant influence on the performance and degradation of PV panels (Aboagye, Gyamfi, Ofosu, & Djordjevic, 2022; Ameur, Berrada, Bouaichi, & Loudiyi, 2022). There are some key factors related to climate that affect PV panels. These involve the identification of the climate zones, using the Köppen-Geiger climate classification map; According to the map in Fig 2, the climate is classified into five vegetation zones as follows: zone (A, blue colour) - equatorial/tropical, zone (B, deep red colour) - arid, zone (C, green colour) - warm temperate, zone (D, light blue colour) cold temperate or snow and zone (E, gray colour) - polar.

Data on PV degradation studies were collected based on this classification and the outcomes of this study are summarised below:

Zone (A) - The degradation of PV panels is much more rapid and harsh in the hot and humid conditions in zone A, tropical climates compared to other ambient conditions. Studies have shown that in zone A delamination is more frequent and severe, and de-bond energy of ethylene-vinyl acetate copolymer (EVA)/glass is reduced from 2.15 kJ/m2 to 1.75 kJ/m2 when temperature increases to 25 °C - 50 °C, and corrosion is accelerated by the humidity ingress and high temperature

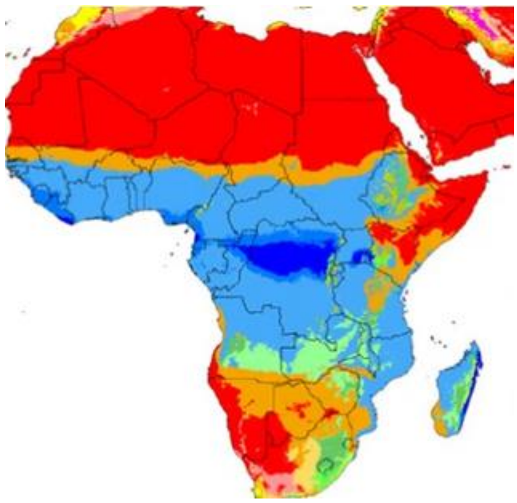

Fig 2. Köppen-Geiger climate classification map for Africa (Beck et al., 2023)

(Czanderna & Pern, 1996; Knausz *et al.*, 2015; Ottersböck, Oreski, & Pinter, 2016; Urrejola *et al.*, 2016).

Zones (B) – This zone is known as arid or desert, characterised by hot and dry climatic conditions, and appears to be the most harsh environment for PV panels. The PV panels are subjected to harsh climatic stress factors, such as temperature cycles, sand and dust, and high solar and UV irradiation (Bouraiou *et al.*, 2015). The PV panels in zone (B) are commonly associated with discolouration of the EVA encapsulant, coupled with delamination above the cell, and a certain level of corrosion, as failure modes.

Zones (C) - EVA discolouration, snail tracks phenomenon, encapsulant delamination and corrosion resulting from moisture ingress are major failure types in Zone (C), warm and temperate climate (Allen, Edge, Mohammadian, & Jones, 1994; Urrejola *et al.*, 2016).

Zones (D&E) – the (D) and (E) zones are snow (D) and polar climates (E), respectively, and are associated with lower temperatures that prevent thermal degradation modes. However, the climates are known to cause mechanical stresses, such as glass breakage, wind stresses, high snowfall, cell cracks, frame breakage or bending. Other failures related to these zones are EVA compliance, brittleness of EVA because of lower modulus of elasticity, seal-edge adhesives embrittlement and stability reduction (Dhere & Raravikar, 2001; Köntges, Altmann, Heimberg, U. Jahn, & Berger, 2016).

Solar panel manufacturers offer a power warranty that guarantees a minimum output of about 80% or more after 25 years. Solar Panel degradation is an important factor to consider when choosing and installing solar panels, as it affects the savings and return on investment of a solar system. The degree of degradation in the second year ($Y2_{dgr}$) is calculated using equation (1 and 2):

$$Y2_{dgr} = \frac{100*(Y1_{PVOUT} - Y2_{PVOUT})}{Y1_{PVOUT}} \quad (1)$$

$$Yn_{dgr} = \frac{100*(Y(n-1)_{PVOUT} - Yn_{PVOUT})}{Yn_{PVOUT}} \quad (2)$$

Where $Y1_{PVOUT}$ is the power generated in the first year; $Y2_{PVOUT}$ is the power generated in the second year.

2.3.3. Inverter failure

The inverter is a crucial component of a PV system as it converts the DC electricity produced by the solar panels into AC electricity for use in homes or incorporation into the electrical grid. Inverter failures can occur due to manufacturing defects, overheating, or age-related issues. When the inverter fails, the system may not produce any electricity, and it will require repair or replacement. Estimating the failure rate of a PV system inverter can be challenging as it depends on various factors, such as the quality of the inverter, its operating conditions, maintenance practices, and environmental factors. Theoretically, inverter or clipping loss ($INV_{clippingloss}$) is defined as the difference between the simulated power ($P_{simulated}$) and the actual power of the inverter (P_{actual}), as depicted by equation (3) (Pandey, Kumar, & Panwar, 2019).

$$INV_{clippinglos_s} = P_{simulated} - P_{actual} \quad (3)$$

The determination of simulated power is expressed in the equation 4.

$$P_{simulated} = PR_{projected} * DC_{cap} \quad (4)$$

Solar PV clipping loss refers to the reduction in energy production when a PV system operates at its maximum power capacity, also known as its "clipping point." Clipping occurs when the available sunlight exceeds the capacity of the inverter to convert it into usable electricity. This situation commonly arises when a solar PV system is oversized or during periods of exceptionally high solar irradiation. Solar PV systems are designed to operate within a specific power range. When sunlight intensity exceeds the system's maximum power capacity, the excess energy cannot be utilized effectively. Instead, it is "clipped" or discarded, resulting in a loss of potential electricity generation.

The Earth's atmosphere acts as a filter for solar radiation, and various components in the atmosphere, such as water vapour, aerosols, and clouds, can scatter or absorb sunlight rays (Jathar et al., 2023; Raillani, Chaatouf, Salhi, Amraqui, & Mezrhab, 2022; Raillani, Chaatouf, Salhi, Bria, et al., 2022). These processes result in a reduction in the amount of solar radiation reaching the Earth's surface. Tiny solid or liquid particles suspended in the atmosphere, known as aerosols, can scatter and absorb solar radiation. Natural sources of aerosols include volcanic emissions and dust storms, while human activities like industrial pollution also contribute to aerosol formation. Increased aerosol concentrations can lead to reduced solar irradiance. Clouds reflect and scatter solar irradiation, preventing it from reaching the Earth's surface. The amount and type of clouds present in the atmosphere vary, affecting the overall solar irradiance levels. Overcast skies result in higher irradiance loss compared to clear skies. It is crucial to consider these factors when assessing the solar potential of a particular region or estimating energy generation from solar installations.

2.4. Photovoltaic system quality parameters

2.4.1. Performance ratio (PR)

The performance ratio (*PR*) is a metric used to evaluate the efficiency and performance of a PV system. It is defined as the ratio of the actual energy output of the PV system to the theoretical maximum energy output under ideal conditions. The performance ratio takes into account various factors that affect the overall efficiency of the PV system, including temperature losses, shading, module soiling, and system availability. A higher performance ratio indicates better system performance and efficiency, while a lower ratio suggests that the system is underperforming due to various factors. Performance ratio equally depends on other factors, such as system design, components quality, maintenance practices, and environmental conditions. Therefore, it is important to monitor the *PR* regularly to identify any deviations and take corrective actions if necessary, to optimize the PV system's performance. The performance ratio is expressed as a percentage (Williams S. Ebhota & Pavel Y. Tabakov, 2022a, 2022b). Mathematically, *PR* is expressed by Eq 5-8:

$$PR = \frac{PVOUT * I_{stc}}{GTI * DC_{cap}} \quad (5)$$

$$PR = \left(\frac{PVOUT}{(C_{Installed} * Y_{Ref})}\right) * 100 \quad (6)$$

$$PR = \frac{PVOUT}{PVOUT_{est}} \quad (7)$$

$$PVOUT_{Est} = GTI*A*\%eff \quad (8)$$

Where *PVOUT* is the actual energy produced by the PV system over a given period (measured in kilowatt-hours, kWh); I_{stc} is the irradiance at STC (1000 W/m^2); DC_{cap} is the direct current (DC) capacity (W) of the PV system; $C_{Installed}$ is the rated capacity of the PV system, representing the maximum power output under standard test conditions (kilowatts, kW); Y_{Ref} is the expected energy output of the PV system under ideal conditions (kilowatt-hours per kilowatt-peak, kWh/kWp); and *% eff* is PV module efficiency and *A* is PV panel surface area (m^2).

2.4.2. Capacity factor

The capacity factor (*CF*) is a parameter to measure the actual energy production of a PV system as a percentage of its maximum potential production over a given period. It represents the average power output of the PV system relative to its installed capacity. The *CF* indicates how effectively a PV system is utilised and how well it performs relative to its installed capacity. A higher *CF* indicates that the system is operating efficiently and generating a significant amount of energy relative to its capacity. Conversely, a lower *CF* suggests that the system is underperforming or experiencing downtime, resulting in lower energy production compared to its installed capacity. Several factors influence CF, such as location-specific solar irradiation, shading, temperature losses, maintenance downtime, and system availability. The *CF* is estimated using the expression in equation (9):

$$CF = \left(\frac{PVOUT}{(C_{Installed} * T_{Total})}\right)*100 \quad (9)$$

Where T_{Total} is the total duration of the specified period for which energy production is considered in hours.

Different locations and system configurations yield different capacity factors and the average CF of a PV system ranges from 10-25% (IEA, 2018; Whatnextnow, 2023). Therefore, it is crucial to consider the capacity factor when evaluating the performance and efficiency of a PV system or comparing it with other renewable energy sources or conventional power generation technologies. However, the application of a tracking facility and larger inverters help energy input and increase the PVOUT of a PV system, respectively. The value of CF could surpass 25% and get to above 30% (Al-Kouz, Al-Dahidi, Hammad, & Al-Abed, 2019; Boretti, 2018; EIA, 2019b)

*2.5. Photovoltaic software applications: Solargis and PV*SOL*

The computation of irradiance and PV system design and performance evaluation are complex activities that involve heavy data and complicated mathematical models. However, several PV software applications have developed that when deployed they make these complex processes have been made simpler, faster and more accurate. Some of these applications are REScreen, PVstst, Solargis, PV*SOL and so on. Both Solargis and PV*SOL play crucial roles in the PV industry. Solargis and PV*SOL are slightly different:

PV*SOL: This software specialises in the design and simulation of photovoltaic systems. It allows users to model, simulate, and optimise PV systems on various scales, from individual installations to large-scale solar arrays. PV*SOL provides own consumption, grid feed in, and avoidable CO2 emissions.

Solargis: This software utilises a comprehensive approach based on satellite data, meteorological information, and modelling algorithms to provide accurate and high-resolution solar radiation and photovoltaic energy potential assessments. It combines data from various sources to offer detailed solar radiation maps, historical data, and forecasts, enabling users to assess potential energy generation for a location.

In PV system simulation, Solargis categorised the energy losses into (Solargis, 2023):

i. Static losses - mismatch between PV panels, panel surface pollution, and cable losses.

ii. Dynamic losses – this class involves irradiance/temperature conditions-based losses, which are functions of day and seasons variations

The energy loss due to Global irradiation striking on a tilted plane of PV panels is estimated from these parameters GHI, DNI, terrain albedo, and immediate sun position within sub-hourly time intervals, represented in equation (10).

$$GTI = fDIFF(GHI, DNI, SE, SA, Albedo) \quad (10)$$

Shading influenced by buildings is a function of several parameters as shown in equation (11)

$$GTISHADED = fSHAD(GTI, SE, SA, Horizon) \quad (11)$$

Where *SE* and *SA* are Sun altitude (elevation) angle (°) and Sun azimuth angle (°), respectively.

3. Method of the study

The method of this study followed a systematic arrangement of site description, generation of meteorological information, PV system configuration, simulation, and report generation. A hypothetical 10-kWp rooftop crystalline silicon PV system was installed at specific locations identified by latitudes and longitudes. Optimisation based panel's orientation and tilt were employed to assess the PV potential at chosen sites across SSA. The site-bearing system combined with meteorological data, as shown in Fig 3, were inputted to generate PV system's performance evaluation parameters at the selected locations. Two computational modelling tools, Solargis Prospect and PVSOL applications, were exploited. The two applications were chosen because of their accessibility, precision, user-friendly interface, and detailed reporting capabilities. Solargis was utilised for solar PV potential and system's performance assessments while PV*SOL was deployed for CO_2 emissions estimate. The data extracted from the reports was used to scrutinise and analyse the solar PV's potential, exploitation level, estimate the system's performance, and evaluate the avoidable CO_2 emission because of the deployment of a RE system. The information was used to investigate and evaluate the influence of ambient, meteorological, system, and climatic parameters on energy losses in PV systems. The systematic structure of the method is illustrated in Fig 3.

3.1. Computational modelling of a PV system

This section addresses all technical facets of the PV system, spanning from evaluating its potential to configuring the hypothetical installed capacity of a 10-kWp crystalline silicon (c-Si) PV system for performance assessment. This involves a

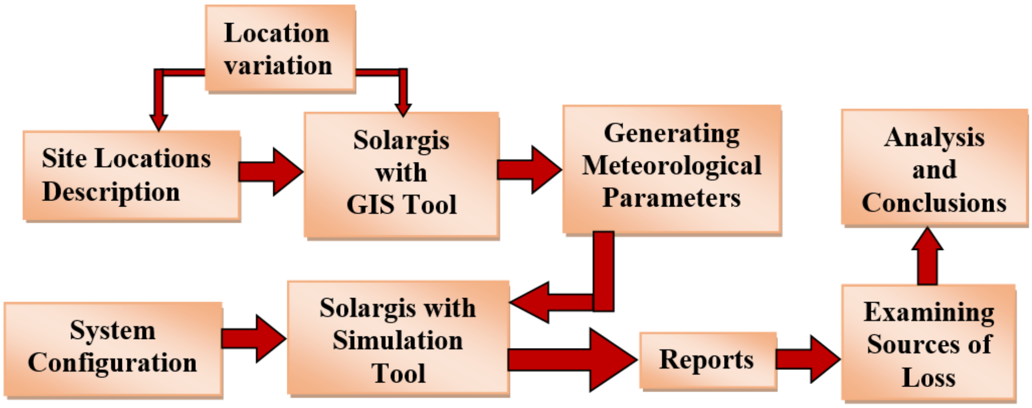

Fig 3. The methodology employed in this study

Table 1
Site location description

Country/Region	City	Latitude (°)	Longitude (°)	Azimuth/Tilt (α/β) °
Nigeria/West Africa	Abuja	09.064331	007.489297	180/13
Ethiopia/East Africa	Addis Ababa	09.0000	038.45	180/15
DRC/Central Africa	Kinshasa	-04.321706	015.3125	0/4
South Africa/Southern Africa	Pretoria	-25.745928	028.18791	0/28
Libya/North Africa	Tripoli	32.896672°	013.177792	180/29

thorough elucidation of the site's characteristics, PV system setup, and simulations based on the chosen locations. The ensuing reports from these locations were utilised to scrutinise, compare, and discuss various sources of PV losses, such as solar irradiance and inverter losses. Additionally, it encompasses an analysis of PV panel degradation and explores how ambient conditions impact the quality of PV potential and system performance.

3.2. Site location description and system configuration

The c-Si PV panels were mounted on a large tilted roof of a building with a provision for Azimuth and tilt angles adjustable feature for optimal configuration. The panels do not shade each other, and the panels' Azimuth and tilt angles are homogeneous. The system was directly connected to a low-voltage grid through an inverter, and distribution transformer without electricity storage. The details of the selected locations, their coordinate systems and Azimuth and tilt angles for optimal configuration are presented in Table 1.

4. Results and discussion

4.1. Energy loss in terms of GHI and GTI

Considering Fig 4(a), the highest GHI gain (215.4 kWh/m^2) in transforming to GTI was observed in the site in Pretoria location followed by the location in Tripoli (201.8 kWh/m^2) while the least was found in Kinshasa location (3.6 kWh/m^2). The size of GHI gain has an element of proportionality with the GHI received. This relation can be spotted in Kinshasa and Abuja locations; they are first and second in descending order in both the amounts of GHI received and the energy gained. In the case of GTI, loss was the obvious; the highest and lowest losses were observed in Tripoli (130 kWh/m^2) and Kinshasa (103 kWh/m^2). The same relation between the received and gained irradiance as observed in GHI, exist in GTI. Element of proportionality relation was seen in Kinshasa and Abuja locations; they are first and second in descending order in both the amounts of GTI received and lost. The amount of gained and lost energy in terms of GHI and GTI are location dependent.

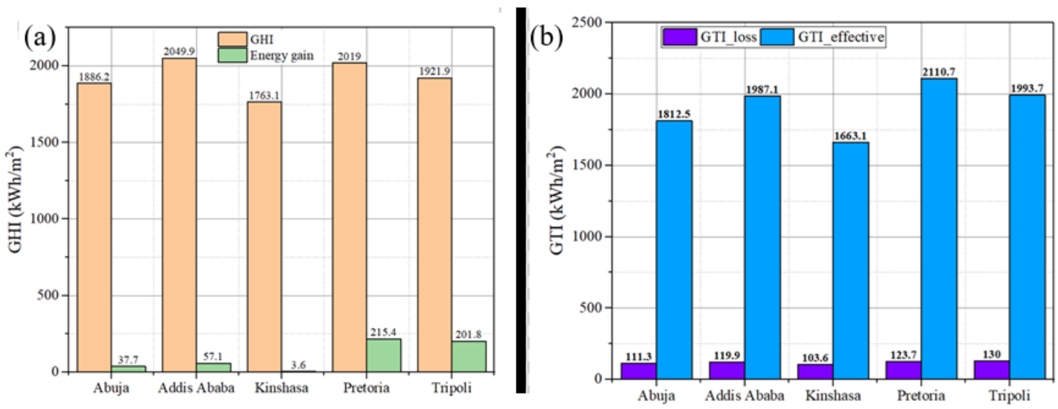

Fig 4. Energy loss in terms irradiance (a) GHI loss; (b) GTI loss

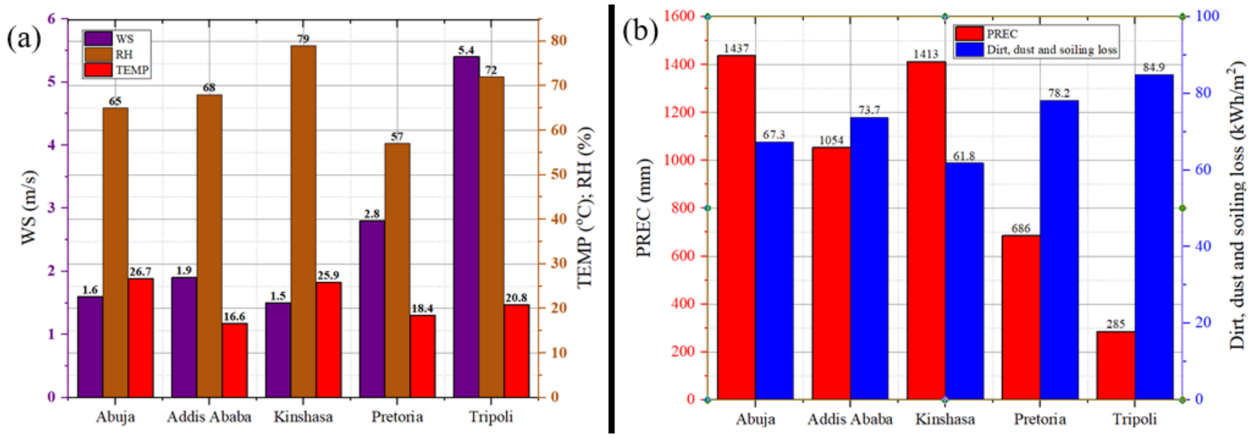

Fig 6. Irradiance loss facilitators (a) WS, RH, and TEMP; (b) PREC, dirt and dust, and soiling

Considering the data obtained from the study's report, the summation of dirt, dust, and soiling losses is observed to be highest (84.9 kWh/m^2) and least (61.8 kWh/m^2) in Tripoli and Kinshasa, respectively, as presented in Fig 5(a). The loss due to angular reflectivity almost follow the same trend with the summation of dirt, dust, and soiling losses. The highest (46.1 kWh/m^2) and lowest (41.8 kWh/m^2) angular reflective losses were observed in Addis Ababa and Kinshasa locations, respectively. All the locations have substantial angular reflective losses, which means there is reduction in the PV system's efficiency due to the angle at at which sunlight strikes the PV panels. The discrepancy in angular reflective losses between among the locations is attributed to environmental factors specific to each location. Various aspects, such as the sun's angle, surface properties, atmospheric conditions, and other geographical or climatic elements influence the efficiency of sunlight absorption by the PV panels.

The gross and effective GTI were presented in Fig 5(b) and the highest (2234.4 kWh/m^2) and least GTI were recorded in Pretoria and Kinshasa, respectively. This implies that Pretoria and Kinshasa have the highest and lowest PV potential, respectively.

4.2. Influence of ambient conditions on irradiance loss

Apart from natural phenomena, and human activities, several atmospheric conditions contribute to solar irradiance loss. The information extracted from the reports of this study shows that the magnitudes these vary across the site locations. Several ambient conditions, such as TEMP, WS, RH, PREC, dirt and dust, as shown in Fig 6, contribute to solar irradiance loss or attenuation and the subsequent PV potential. The high temperature and WS observed in Abuja and Tripoli locations are responsible for their relative irradiance losses. The annual average temperature of Abuja is above 25 °C and at higher temperatures module's PCE and power output decrease. The temperature coefficient, supplied by manufacturers, indicates the percentage reduction in power output for every degree Celsius increase in temperature above 25 °C, which is the standard test condition. Other negative impacts of high temperatures are higher resistive losses, an increase in the system's voltage, and decreased inverter efficiency. Although rainfall provides cleaning and temporal cooling effects on PV panels, heavy precipitation can cause partial shading, mechanical stress, and electrical insecurity to the PV system. This partial shading can reduce the amount of light reaching the shaded cells, resulting in a decrease in overall power output.

In the case of the location in Tripoli, the relatively high WS will trigger dirt and dust and spread them on the surfaces of the PV panels. The most obvious effect of dirt and dust is that they block sunlight from reaching the PV cells. This reduces the amount of light absorbed by the cells and, consequently, decreases the electricity generation of the PV system. The reduction in efficiency ranges from minor to significant, depending on the amount and type of dirt/dust accumulated. If the dirt and dust accumulate uniformly across all solar panels, the reduction in power output is more manageable as the whole system's performance is affected similarly. However, non-uniform soiling, like shadows from nearby objects or partial shading, can result in more severe efficiency losses in specific areas.

4.3. Photovoltaic system losses

This section addresses the primary categories of losses that impact the overall efficiency of c-Si PV systems in the conversion of sunlight into electricity. The main losses in c-Si PV systems encompass conversion efficiency losses, temperature-related losses, shading and soiling losses, mismatch losses, and light-induced degradation (LID). According to the data extracted from the study report, inverter and radiation conversion losses constitute the largest portion of the total PV system losses, as illustrated in Fig 7(a). Other significant contributors to energy losses in a PV system are detailed in Fig 7(b). The investigation revealed that Inverter energy losses ranged from the highest at 83.1 kWh/kWp in Pretoria to the lowest at 57.7 kWh/kWp in Kinshasa. Meanwhile, radiation conversion losses varied from the least at 57.4 kWh/kWp in Addis Ababa to the highest at 212.3 kWh/kWp in Tripoli.

Furthermore, the greatest and least mismatch losses were observed in Tripoli (35.5 kWh/kWp) and Kinshasa (22.4 kWh/kWp), respectively. Additional pertinent sources of energy losses in PV systems are spectral correction and transformer and cabling losses, depicted in Fig 7(b). The lowest and highest spectral correction losses were in Abuja (0.3 kWh/m^2) and Addis Ababa (31.8 kWh/m^2) locations, respectively. The spectra correction loss in Abuja is significantly lower compared to Addis Ababa, indicating a more optimal or efficient performance of the PV system in Abuja in this context. This means that the PV system experiences comparatively minor losses due to factors, such as spectral response mismatch, temperature effects, shading, and other inefficiencies. The variance in spectra correction losses across the locations, suggests differences in their efficiency in

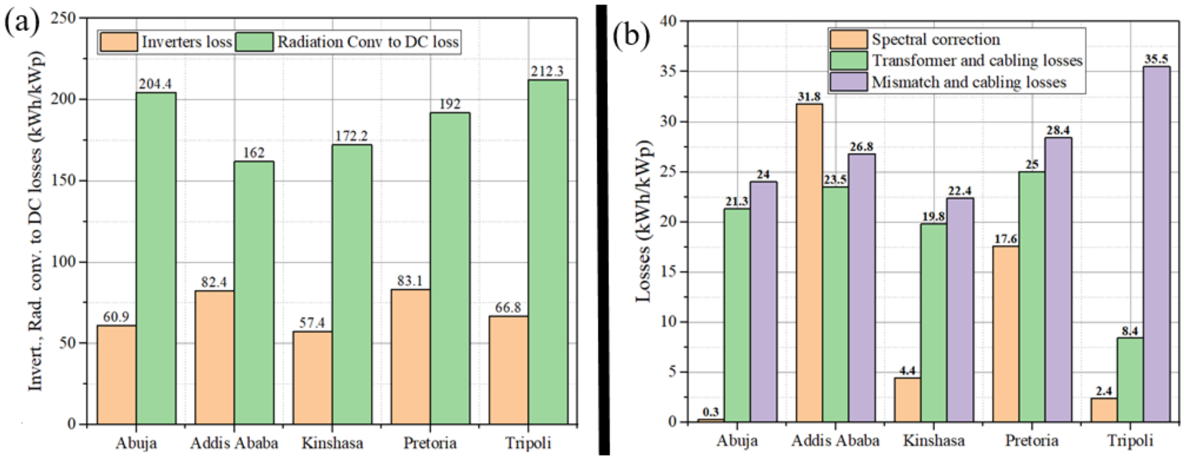

Fig 7. Primary losses in c-Si PV system (a) Inverter and radiation conversion to DC losses; (b) Spectral correction, transformance and cabling, mismatch and cabling losses.

capturing and utilising sunlight by the PV systems. Site-specific environmental and geographical factors are likely responsible for the observed dissimilarities in the spectra correction losses between these locations.

The factors contributing to energy losses in PV systems, as identified by (Bruce, 2023), include reflective losses, mismatch losses, temperature-related losses, shading losses, soiling and contamination, and angle of incidence losses. Furthermore, other contributors encompass angle of incidence losses, non-uniform illumination, electrical and thermal losses, spectral response mismatch, and light-induced degradation (LID). Understanding and accounting for these factors is crucial in photosensitive related design, engineering, or any situation where precise control or measurement of light at different angles is essential. It enables the minimisation or compensation for losses and ensures accurate and predictable behaviour in solar PV systems.

Solar potential and the performance of PV systems are assessed by the amount of irradiance striking the PV panel, measured in kWh/m^2, and the electricity generated, measured in kWh/kWp, respectively. In reference to Fig 8(a), the Pretoria location stands out with the highest effective GTI at 2110.7 kWh/m^2 and startup PVOUT at 1764.5 kWh/kWp. Conversely, the Kinshasa location exhibits the least effective GTI (1663.1 kWh/m^2) and startup PVOUT (1395.8 kWh/kWp). Additionally, as indicated in 10(b), Pretoria claims the highest technically available PVOUT at 1729.2 kWh/kWp and specific average PVOUT at 1616.3 kWh/kWp. Conversely, Kinshasa records the lowest technically available PVOUT (1729.2 kWh/kWp) and specific average PVOUT (1616.3 kWh/kWp). When arranging the examined site locations in a descending order, the sequence is Pretoria, Tripoli, Addis Ababa, Abuja, and Kinshasa. Nevertheless, it's noteworthy that the implementation of PV systems is technically viable in the latter two countries, Abuja and Kinshasa, as they possess sufficient solar PV potential.

4.4. Estimation of Solar Panel degradation

The degradation in the context of c-Si PV technology refers to the gradual reduction in the performance or efficiency of solar panels over time. This decline can be attributed to various factors and mechanisms that affect the functionality of the c-Si-based solar cells. These factors include material degradation, environmental elements, mechanical stress, light-induced degradation, and manufacturing variations and defects. The data obtained from the study shows that all the site locations possess the same degradation rate trend, as shown in Fig 9(a). It was observed that the c-Si PV panel degraded by 0.8% and 0.5% in the first year and successive 24 years, respectively. This indicates that during the initial year of operation, the efficiency or energy output of the crystalline silicon PV panel decreases by 0.8% compared to its original performance. The panel's efficiency diminishes by 0.8% within the first year of operation. For the subsequent 24 years after the first year, the panel's efficiency decreases annually by 0.5%. This means that every year after the first, the panel's efficiency reduces by 0.5% relative to the previous year's performance. This resulted in an

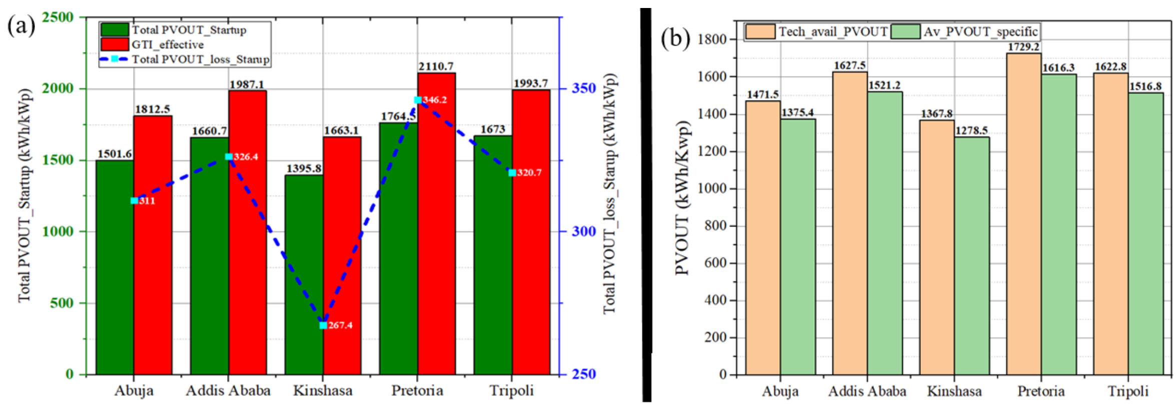

Fig 8. Photovoltaic potential and system performance (a) effective GTI and total PVOUT startup; (b) Technically available PVOUT and specific average PVOUT.

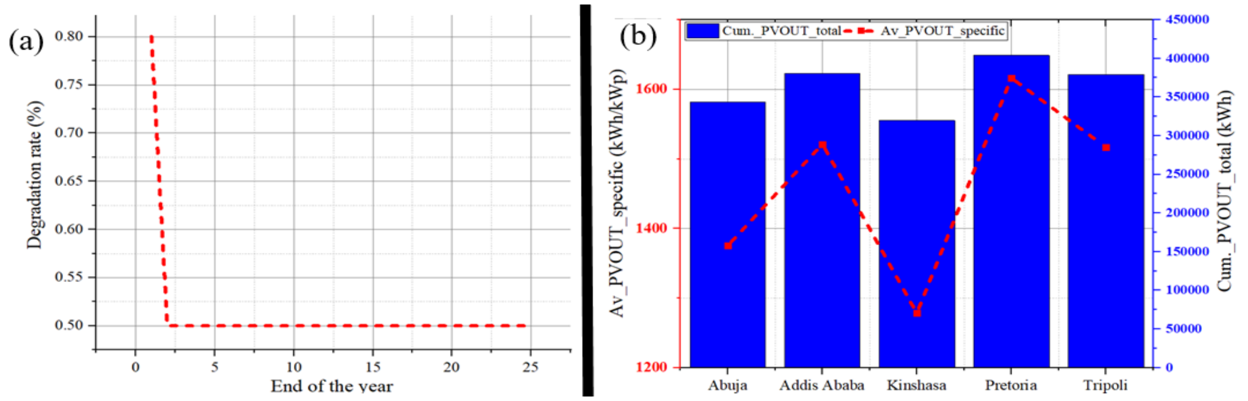

Fig 9. (a) Degradation curve of c-Si PV panel; (b) twenty-five average specific and cumulative PVOUT values

annual average of 0.5% and a cumulative 12.8% degradation rate. The cumulative degradation rate of 12.8% represents the total overall reduction in efficiency or performance of the PV panel since its installation for 25 years.

The given degradation rates provide insight into the anticipated reduction in the PV panel's performance over time. These values are essential for predicting the panel's efficiency decline and planning for maintenance or potential replacements in solar installations to ensure sustained and optimal energy output over the panel's lifetime. Understanding and mitigating degradation in c-Si PV panels are essential to prolong their lifespan and maintain their optimal performance. Continuous research, quality manufacturing standards, better materials, and improved engineering techniques are crucial to minimize the impact of degradation in these solar panels.

The specific average and cumulative PVOUT values over 25 years for PV electricity produced by the installed capacity of the investigated PV systems are depicted in Fig 9(b). The magnitudes of these parameters exhibit a similar trend. The lowest cumulative PVOUT (31,9629.5 kWh/kWp) and the highest (40,4074.5 kWh/kWp) were observed in Kinshasa and Pretoria locations, respectively. Cumulative PVOUT represents the total energy generated by a PV system throughout its expected operational lifespan of 25 years, encompassing the sum of annual energy outputs. For the average specific PVOUT, the lowest (1,278.5 kWh/kWp) and the highest (1,616.3 kWh/kWp) values were recorded in Kinshasa and Pretoria locations. In practical terms, the 25 years PV system specific output average serves as a performance metric, offering an estimation of the average energy production efficiency of a solar installation over a quarter-century. This metric considers factors such as the anticipated degradation rate of the solar panels, environmental conditions, maintenance practices, and the quality of the components employed in the PV system.

4.5. Quality of PV potential and system performance

The annual sum of GTI, *PVOUT*, and twenty-five years cumulative total *PVOUT* by each of the PV systems in the selected locations are presented in Table 2 and Fig 10(a). The site location in Pretoria is leading the table, closely followed by the one in Addis Ababa with Kinshasa recording the lowest. Several factors, such as relatively low *WS, RH,* and *TEMP* favour Pretoria's PV potential and performance status. Energy losses attributed to both climate, meteorological, and system factors were observed, and the degree of loss is relative to locations and magnitude of GTI of each location.

A city was selected from each of the five zones that make up SSA for the PV system site location. The purpose of choosing a city from each zone is to enable the PV potential and system performance evaluation of that zone to be extrapolated from the results of the selected city. The information in Fig 10 shows the cities (countries/zones) evaluated have abundant sunlight and are well-suited for PV electrification projects. In addition, the high potential and performance of PV systems across SSA can be seen in Fig 10(a). Considering Fig 10(b), the annual average PR and CF profiles of each of the PV systems of the selected locations, show that locations in Pretoria (77.4%/19.7%) and Kinshasa (77.4%/15.6%) possess the highest and least quality of PV, respectively.

The potential and performance of PV a system vary with season and location. This is seen in Fig 11, showing the monthly total *PVOUT* and PR profiles of PV systems at the selected locations. In the case of Pretoria, the highest of both *PVOUT* and PR were recorded in August (winter, daytime

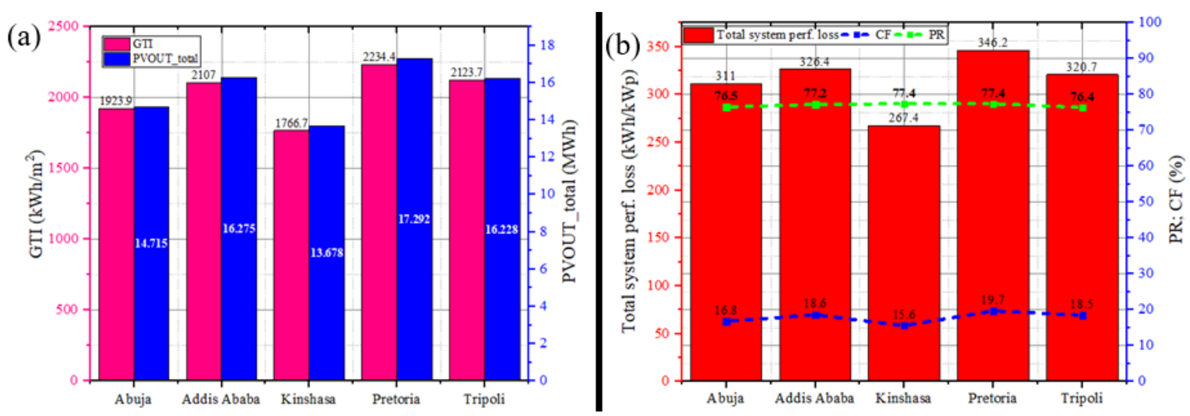

Fig 10. Quality of PV potential of the chosen locations (a) GTI and *PVOUT*; (b) Energy loss and PR.

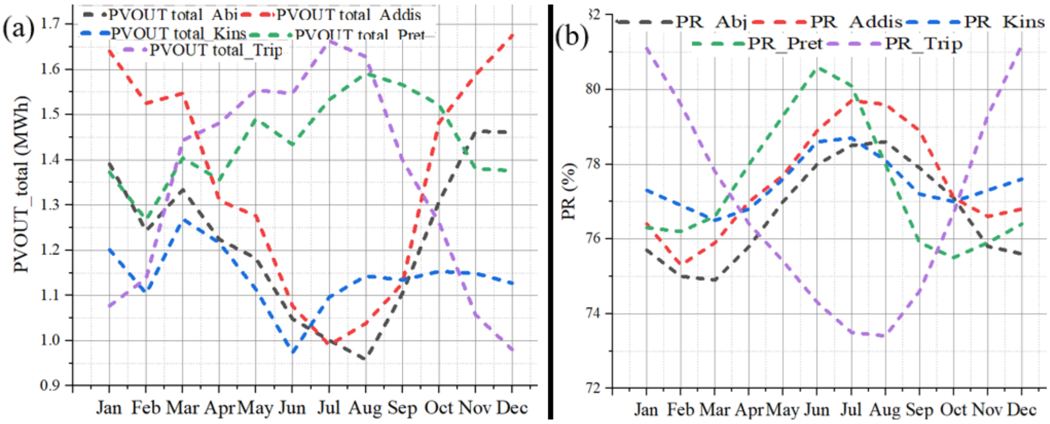

Fig 11. (a) Monthly total PV power output (PVOUT); (b) Performance ratio (PR) of the different locations

TEMP = 18 °C to 22 °C); it means that winter favours PV energy generation more than any other season in Pretoria. A contradiction is seen between *PVOUT* and PR in Tripoli; the highest *PVOUT* is in July-August (summer, TEMP ≥30°C) while the lowest PR was observed in July-August; it means despite the highest yield of energy in July-August, the quality of production is least in that period. In this context, the quality of production is highest in December-January (winter, TEMP = 10°C to 18°C), which means winter favours PV generation more than any other season in Tripoli. For Abuja (wet season, daytime TEMP = 25 °C to 30 °C), Addis Ababa (rainy season, daytime TEMP = 20 °C to 23 °C), and Kinshasa (dry season, daytime TEMP = 25 °C to 28 °C) in Fig 11(a), the energy yield is highest in June – August while in Fig 11(b), the locations have the highest PR.

5. Conclusions

In essence, solar PV technology will persist in revolutionising society by steering the transition to RE, enhancing energy accessibility, generating employment, lowering energy expenses, fostering energy self-sufficiency, driving technological innovation, and promoting awareness of sustainability. Combining PV technology with other RE sources, energy efficiency measures, and sustainable practices can significantly contribute to achieving the 1.5°C goal by 2050. However, the issue of energy loss in solar PV systems is a notable concern due to its impact on overall efficiency and economic viability. A comprehensive study on solar PV energy loss is crucial for maximising the benefits of solar energy, enabling system optimization, ensuring economic viability, complying with policies, and advancing RE technology. This study focuses on evaluating losses associated with PV potential and systems in various locations across SSA, including Abuja, Addis Ababa, Kinshasa, Pretoria, and Tripoli. The study identified key sources of energy losses, such as PV panel degradation, inverter failure, angular reflectivity, solar irradiance loss, shading issues, faulty wiring, and lightning strikes. Notably, inverter losses were highest in Pretoria and lowest in Kinshasa, while PV potential in terms of kWh/m^2 was highest in Pretoria and lowest in Kinshasa.

The findings emphasise that energy loss sources vary with locations and irradiance magnitudes. Pretoria, with the highest GTI at 2110.7 kWh/m^2, recorded the highest PV system energy loss (346.2 kWh/kWp), whereas Kinshasa, with the least GTI at 1663.1 kWh/m^2, had the least energy loss (267.4 kWh/kWp). Reducing these losses through improved technology, design, installation practices, and ongoing maintenance is crucial for enhancing the overall performance and energy output of crystalline silicon PV systems. Manufacturers and engineers continually strive to minimize these losses, optimizing the efficiency of solar panels and improving the cost-effectiveness of solar energy generation. Therefore, implementing measures such as regular maintenance, measuring inverter efficiency, optimal system design, use of bypass diodes, deploying high-quality PV panels, employing MPPT technology, utilizing energy storage devices, regular monitoring, and adopting energy-efficient appliances and practices becomes imperative to mitigate solar PV system energy losses.

It is imperative to minimise solar PV energy losses as it essential for economic viability, environmental sustainability, and the widespread adoption of solar energy as a key component of the global energy mix. It aligns with broader goals of combating climate change, promoting energy security, and fostering a transition to a more sustainable and resilient energy infrastructure.

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