



# Floating Photovoltaic Systems: Expanding Renewable Alternatives to Combat Greenhouse Gas Emissions

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**Abstract** – Extreme weather events like droughts, floods, heatwaves, and cyclones are increasingly linked to climate change, leading to fatalities, infrastructure damage, and the displacement of thousands. CO<sub>2</sub> emissions primarily drive this climate change from burning fossil fuels. South Africa (SA), the highest CO<sub>2</sub> emitter in Africa, heavily relies on coal, which accounts for nearly 85% of its emissions. However, SA also has significant but underdeveloped solar energy potential. Expanding solar PV is crucial for SA and other African nations to address energy shortages, reduce GHG emissions, enhance energy security, stimulate economic growth, create jobs, and achieve long-term cost savings. The study includes a computational modelling case study to evaluate PV potential and system performance, comparing onshore and offshore scenarios. It reports a Global Tilted Irradiance (GTI) of 1866 kWh/m<sup>2</sup> for land-based PV (LPV) and 1797 kWh/m<sup>2</sup> for FPV, with a Levelised Cost of Energy (LCOE) of \$0.04612/kWh for LPV and \$0.05664/kWh for FPV, respectively. The results suggest that the 10-kWp LPV system slightly outperforms the FPV system, though both are within acceptable performance ranges because of harsher offshore conditions. The paper proposes hybrid RE systems including FPV to improve SA's grid stability and efficiency.

**Keywords:** South Africa's energy consumption; South Africa's CO<sub>2</sub> emissions; Land photovoltaic (LPV); Floating photovoltaic (FPV) systems

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## I. Introduction

Photovoltaic (PV) systems are essential for harnessing renewable energy, but their performance and reliability are significantly influenced by climatic conditions. High temperatures, for instance, can reduce the efficiency of PV modules due to thermal losses, while excessive humidity may lead to corrosion of electrical components. Similarly, environmental factors such as dust, shading, and precipitation can decrease energy output and accelerate system degradation. On the other hand, PV systems contribute to mitigating climate change by generating clean energy, reducing reliance on fossil fuels, and lowering greenhouse gas emissions. Understanding the relationship between PV faults and climate is crucial for optimizing system performance, improving

durability, and ensuring the long-term viability of solar energy solutions in various regions.

Extreme weather events like droughts, floods, heatwaves, and cyclones are increasingly linked to climate change, leading to fatalities, infrastructure damage, and the displacement of thousands. The Intergovernmental Panel on Climate Change's 2022 report on "Impacts, Adaptation, and Vulnerability" highlighted that many African regions are among the global hotspots for human vulnerability to climate change [1]. In South Africa (SA), the provinces of KwaZulu-Natal and Eastern Cape have experienced numerous devastating floods and landslides triggered by heavy rainfall. Many of SA's cities were built before the realities of climate change were understood, leaving them particularly susceptible to these



impacts. KwaZulu-Natal has faced destructive flooding events in July 2016, May 2017, October 2017, March 2019, April 2019, November 2019, November 2020, April 2023, June 2023, and most recently in January 2024 [2]. In 2022 alone, over 440 people lost their lives, approximately 4,000 homes were destroyed, and road damage caused by the floods was estimated at a minimum of R5.6 billion [3].

Fossil fuel consumption presents a range of significant challenges, including CO<sub>2</sub> and particulate emissions, environmental degradation, economic costs, and resource depletion. Others are energy security and geopolitical tensions, social inequality and displacement, and hindrance to renewable energy (RE) development.

This climate change is primarily driven by CO<sub>2</sub> emissions from burning fossil fuels and SA is the highest CO<sub>2</sub> emitter in Africa. This is attributed to the over-reliance on coal for electricity, which accounts for 83% of CO<sub>2</sub> emissions in SA [4]. The South African Electricity Supply Commission (Eskom) holds a dominant position in power generation, accounting for approximately 85% of the market share [5]. In 2021, about 37.9 BtCO<sub>2</sub> were emitted worldwide and the wealthiest 10% of the global population is responsible for over half of these emissions [6]. On a per capita basis, Africa has the lowest emissions of all continents, with an average of 1 tonne of CO<sub>2</sub> emitted annually per person. For comparison, the average American or Australian emits as much CO<sub>2</sub> in a month as an individual does in Africa yearly [7]. Within Africa, more than 60% of the continent's carbon emissions come from these three countries: SA (435.9 MtCO<sub>2</sub>), Egypt (249.6 MtCO<sub>2</sub>), and Algeria (176.2 MtCO<sub>2</sub>) [8]. The overreliance on coal in electricity generation positioned SA as one of the top 10 GHG emitters globally [9, 10]. In 2022, SA produced 405 MtCO<sub>2</sub> from burning fossil fuels and industrial activities, marking a decrease of approximately 3% from the previous year [11]. However, a lot is required to achieve a substantial reduction as there are still over twenty coal fire-generating plants in SA. Ongoing investments in fossil fuel infrastructure diverts resources from RE development, slowing the transition to cleaner energy sources and extending reliance on fossil fuels, which delays efforts to mitigate climate change and environmental harm.

The shortage of about 5 GW capacity as of mid-2023 is causing significant distress in households and the economy [12]. It currently grapples with urgent challenges, such as widespread power outages. Faced with this predicament since 2022, Eskom resorted to implementing power cuts for 43% of the year, with a record 11.5 TWh in cuts [13]. Dependence on fossil fuels

can create energy security issues, especially for import-reliant countries. Competition for these resources often leads to geopolitical tensions and conflicts.

Fossil fuels are limited resources, and their extraction becomes costlier as reserves dwindle, leading to rising energy costs. This can strain economies, particularly those reliant on fossil fuel imports. The volatility of global oil prices adds to economic uncertainty, affecting national budgets and stability. Electricity prices have surged by 30% since 2020, with gasoline and diesel prices experiencing increases of 29% and 49%, respectively, during the same period [13]. This figure stands over three times higher than the average energy consumption per capita in other Southern African countries, namely Botswana, Eswatini, Lesotho, and Namibia. Economies dependent on fossil fuels are vulnerable to supply disruptions and price shocks from political instability or natural disasters in producing regions.

Studies have long been intrigued by the intersection of energy and the environment. In this context, the panel data from 24 countries within the Organization for Economic Co-operation and Development (OECD), from 1980 to 2014 was used to examine the environmental ramifications of energy utilisation [14]. The study concludes that increasing the use of RE can diminish the ecological footprint. Several studies have examined the relationship between energy consumption and CO<sub>2</sub> emissions in different regions and contexts. A vector error correction model was employed to explore the connection between CO<sub>2</sub> emissions and clean energy consumption in BRICS nations, revealing a bidirectional relationship ([15]). Similarly, research spanning 25 countries of upper-middle and lower-middle income levels from 1990 to 2015 demonstrated that renewable energy (RE) mitigates CO<sub>2</sub> emissions ([16]). In the Mediterranean region, an investigation across nine countries found that renewable electricity usage significantly reduces CO<sub>2</sub> emissions [17]. Conversely, in the Middle East and North Africa, energy consumption was positively linked to carbon emissions, while the relationship varied in Sub-Saharan Africa ([18]). Collectively, these findings align with numerous studies affirming that renewable energy consumption is environmentally beneficial, contributing substantially to reducing CO<sub>2</sub> emissions and fostering a greener environment [19,20].

Renewable energy sources, such as solar, wind, hydroelectric, biomass, and geothermal energy, offer sustainable alternatives to fossil fuels [21]. These sources harness natural processes and resources that are continuously replenished, making them environmentally

friendly and resilient. They also provide opportunities for decentralised energy production, empowering communities and reducing reliance on centralised energy grids

Among the five countries ranked by the Climate Change Performance Index (CCPI), Morocco stands out as the only nation whose renewable energy (RE) electricity capacity share consistently exceeds Africa's average over the past five years. Morocco's RE share grew steadily from 30.54% in 2019 to 36.50% in 2023, surpassing the continental average, which increased modestly from 21.65% to 24.27% during the same period. In contrast, other countries, such as Nigeria, South Africa (SA), Egypt, and Algeria, remain below the African average. Nigeria's RE share improved from 16.47% in 2019 to 20.88% in 2023, while South Africa experienced a gradual increase from 14.24% to 17.04%. Egypt's share grew modestly, reaching 11.17% in 2023, and Algeria recorded the lowest percentages, fluctuating slightly around 2%. Morocco's performance underscores its leadership in advancing renewable energy within the region [22].

In 2020, RE consumption in SA is predominantly fuelled by the following RE technologies: geothermal (1%), direct solar (11%), and bioenergy (88%) [23]. In 2021, SA's RE consumption amounted to  $1.477 \times 10^{17}$  joules. Over the period from 2005 to 2021, utilisation of RE varied between  $1.055 \times 10^{16}$  joules and  $1.477 \times 10^{17}$  joules. Additionally, the consumption level slightly lagged behind the RE production in the country as of 2021 [24]. As of 2023, SA's solar energy capacity stood at 6,164 MW, marking a decrease of approximately 2.6% from the previous year. Between 2013 and 2023, there was rapid solar energy capacity growth, rising from 262 MW to 6,326 MW [25]. This is because the country's unstable power grid has driven residents to seek alternative sources of electricity.

Solar energy is the most sought-after because of its abundance and pattern of spread. Several technologies have evolved to tap this energy. The practical solar energy potential for PV systems in SA is estimated to range between 1,600 to 1,800 kWh/kWp per year [23]. This spectrum indicates conditions ranging from feasible to excellent for PV projects. Combining the average long-term practical yield of utility-scale solar installations, SA's solar potential is approximately 4.51 kWh/kWp/day [26]. South Africa exhibits substantial solar energy consumption, and its solar potential holds promise for further development. Therefore, adequate deployment of solar PV is essential for SA like every other country in SSA for these compelling benefits - mitigating energy shortages, reducing GHG emissions,

enhancing energy security and independence, economic growth and job creation, and long-term cost savings. Other merits are environmental and health benefits, utilizing abundant natural resources, decentralisation and energy access, and aligning with global climate commitments to achieve a sustainable and secure energy future. These solar energy-harnessing technologies are classified into three: PV systems; concentrating solar power (CSP); and solar heating and cooling (SHC) systems. Among solar energy technologies, the PV system is receiving the greatest attention and deployment. and is divided into land (onshore) and floating (offshore) PV systems. One of this study's objectives is to focus on the FPV principle, significance, and econo-technical assessment.

Addressing the challenges of the continued development of RE infrastructure and creating a supportive environment in SA requires coordinated efforts among the government, private sector, academia, and civil society. This study aims to enhance the understanding of PV technology by critically examining its potential and performance. This research exploits solar PV systems as alternatives to fossil fuel and the objectives include the concept of floating/offshore PV systems; designing and simulating PV systems; and using the reports to analyse and evaluate the econo-technical feasibility of LPV and FPV systems in North Durban, SA. It focuses on the role of FPV systems in achieving SA's RE options to replace fossil fuels. The study will satisfy these research questions: what is the level of FPV development in SA? What is the solar PV potential of North Durban, SA, in terms of Global Horizontal Irradiance (GHI) and Global Tilted Irradiance (GTI) for both LPV and FPV scenarios? What is PV system performance in terms of PV output for LPV and FPV scenarios? What is the financial performance of PV systems in terms of capital expenses (Capex), operation (Opex), and the levelised cost of electricity (LCOE) for both LPV and FPV scenarios? Are LPV and FPV systems technically and economically viable in North Durban, SA? Policymakers, PV system developers and installers will find this paper useful

## II. Materials and Methods

### II.1. Floating/offshore PV system concept

The FSPV technology involves installing solar PV panels on water bodies, where they float on pontoons or stilts. These solar modules can be mounted with either single or double-axis tracking systems or at a fixed tilt angle without tracking. The design of the floatation and

anchoring system is crucial for ensuring the stability of the generating system under varying tidal and weather conditions. The floatation platform is made of multiple pontoons, typically made from high-density polyethylene, which offers high tensile strength, and UV stability, and requires minimal maintenance [27]. The floating platform is secured using an anchoring system connected by mooring lines. These anchors are usually concrete blocks set on the water floor or piles drilled into the floor, while the mooring lines are made from nylon or similar materials. Designing the mooring and anchoring system is complex and depends on various factors, including the system's weight, water depth, tides, wind speeds, and ground soil composition [28]. Cables connecting the floating generation system to the electrical grid must accommodate movement and allow for slack. The FPV panels are connected to a combiner box, and then to an inverter, which is subsequently linked to the electricity grid. Additionally, a lightning rod is incorporated into the system designed, connected to all metal frames and structures, and firmly bonded to the earthing system. The major components of FSPV systems are illustrated in Figure 1.

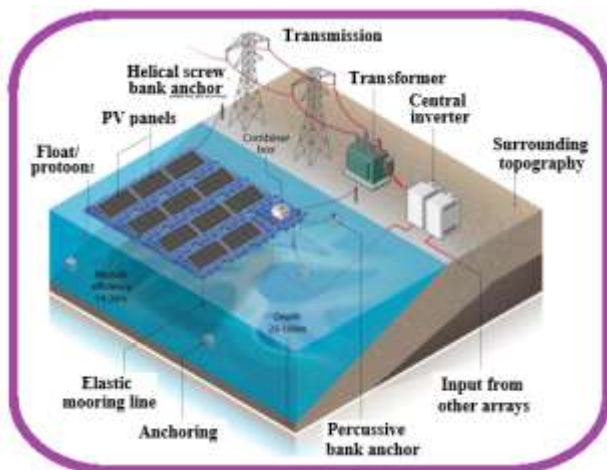


Figure 1. Illustration of a stand-alone FPV system and key features [29].

## II.2. Floating PV system feasibility in SA

Countries worldwide are exploring ways to enhance their current power generation mixes by incorporating inexpensive PV technology to guarantee dependable, cost-effective, and sustainable electricity supplies [30]. Floating solar PV (FPV) is a burgeoning and increasingly feasible utilisation of PV that involves situating systems directly on bodies of water, such as lakes, ponds, or reservoirs. Interest in FPV has surged due to various factors including competition for land use, climate

objectives, energy security, resilience considerations, and other associated advantages of this innovative application. The deployment of FPV is rapidly increasing, with global installed capacity rising from under 1 MW in 2007 to 1,314 MW in 2018 and projected to hit around 13,000 MW by 2022 [31]. The bulk of existing capacity and anticipated growth in the FPV market is concentrated in Asia. Its deployment is propelled by high land costs, limited land availability, and a significant presence of hydropower production linked with reservoirs. China, India, and South Korea stand out as pioneers in floating PV deployment, highlighting their steadfast dedication to sustainable energy solutions. China leads the world in installed FPV capacity, accounting for 52% of the global total, followed by the Taiwan Region at 12% and Japan at 10% [29].

## II.3. Solar photovoltaic potential and system assessment - A case study

This section presents a case study on computational modelling of onshore and offshore PV systems to analyse the dynamics of solar PV potential and the system's performance. This analysis considers the primary irradiance and PV performance parameters, such as GHI, GTI, PVOUT specific and PVOUT total. Additionally, financial components, such as capital expenses (Capex), operation (Opex), and the levelised cost of electricity (LCOE) were considered. This was used to establish the techno-economic competitiveness of the two scenarios. The study's methodology is illustrated in Figure 2.

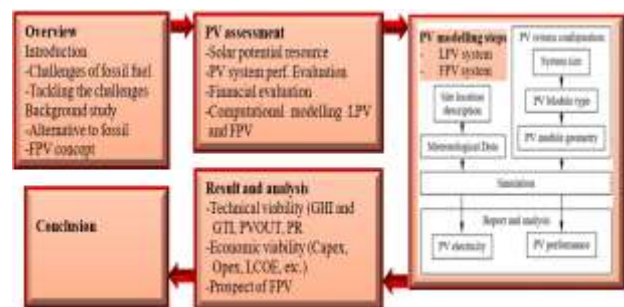


Figure 2. Schematic of the study's methodology

## II.4. Solar resource assessment

Data such as solar insolation levels, solar irradiance, and sun hours are examined to determine the solar energy potential. Determining irradiance entails the assessment of the solar radiation received on a designated surface within a defined timeframe, typically quantified as energy per unit area ( $\text{kWh}/\text{m}^2$ ). Solar irradiance comprises three key components: Global Horizontal

Irradiance (GHI), Direct Normal Irradiance (DNI), and Diffuse Horizontal Irradiance (DIF). These components are mathematically represented as follows [32, 33]:

$$GHI = DNI \cdot \cos(Z) + DIF \quad (1)$$

$$DNI = G_{\text{extraterrestrial}} \cdot \cos(Z) \quad (2)$$

$$DIF = GHI - DNI \cdot \cos(Z) \quad (3)$$

In the equation,  $Z$  represents the solar zenith angle, denoting the angle between the sun and the vertical axis, and  $G_{\text{extraterrestrial}}$  stands for the extra-terrestrial radiation. The connection between solar irradiance and the performance of a PV system is fundamental, as solar irradiance signifies the quantity of sunlight energy per unit area. This factor significantly influences the power output of PV panels. The relationship is straightforward: as solar irradiance increases; the power generation of a PV system tends to increase proportionally. This association is often depicted by the equation [34, 35]:

$$PVOUT = A * GTI * \eta \quad (4)$$

Here, PVOUT represents the power output,  $A$  signifies the area of the PV panel, GTI stands for Global Tilt irradiance, and  $\eta$  denotes the efficiency of the PV panel. This equation illustrates the direct correlation between irradiance and power output.

These computations entail trigonometric functions and rely on the sun's position, which is influenced by factors such as the time of day, date, and geographical location. While these equations offer simplified representations, more complex models account for additional factors, such as atmospheric conditions, albedo (surface reflectivity), and shading effects to provide a more precise assessment of solar irradiance. However, for this study, comprehensive solar resource assessments were conducted using specialised software tools and solar radiation databases.

The solar PV potential assessment aids the determination of the feasibility and effectiveness of implementing PV systems in given locations. This includes site suitability analysis, solar resource assessment, energy demand analysis, financial analysis, technical feasibility study, environmental impact assessment, regulatory and permitting requirements, community engagement and stakeholder consultation.

## II.5. Evaluating Solar PV Efficiency: Parameters, Performance Metrics, and Degradatio

The performance of solar photovoltaic (PV) systems is heavily influenced by various factors, including irradiance, temperature, wind speed, and system degradation. Irradiance, particularly the Global Tilted Irradiance (GTI), is directly proportional to PV power generation, while parameters such as temperature, wind speed, shading, and geographical conditions further impact performance ([36]). Elevated temperatures reduce the efficiency of silicon-based PV panels by 0.4-0.5% per degree Celsius above 25°C, with performance evaluated under Standard Test Conditions (STC) and Nominal Operating Cell Temperature (NOCT) [37-39]. Wind speed helps cool panels to sustain efficiency but must remain within safe limits to prevent damage ([40], [41]). The Performance Ratio (PR), a key metric for assessing PV plant efficiency, has improved significantly over decades, ranging from 70% to 90% in studies, with a typical value of 85% suggested [42-47]) Additionally, PV system degradation influenced by environmental and material factors, results in a gradual reduction in performance, with annual degradation rates critical for long-term predictions [48]. The annual degradation rate is expressed as:

$$R_{\text{ann\_degr}} = \frac{P_o - P_i}{P_o} * \frac{100}{P_{\text{degr}}} \quad (8)$$

$$R_{\text{ann\_degr}} = \frac{C_{\text{degr}}}{P_{\text{degr}}} \quad (9)$$

Where  $R_{\text{ann\_degr}}$  is the annual degradation rate;  $P_o$  is the initial power output;  $P_i$  is the power output after a specific period;  $C_{\text{degr}}$  is cumulative degradation; and  $P_{\text{degr}}$  is the degradation period.

## II.6. Financial parameters of PV systems

The financial parameters of a PV system are crucial indicators that help assess the economic viability and performance of the system. The key financial parameters are Internal Rate of Return (IRR), Return on Investment (ROI), Levelised Cost of Energy (LCOE), Operating Expenditures (OpEx), Capital Expenditures (CapEx), Net Present Value (NPV), and Payback Period, [49, 50]. By evaluating these financial parameters and benchmarks, stakeholders can assess the economic viability of a solar PV system and make informed decisions regarding the choice between onshore and offshore systems. Descriptions of key financial officers are presented in Table 3.

Table 3. Description of the key financial parameters

Parameters	Description
IRR	IRR is a metric used to evaluate the profitability of an investment. It represents the annualized rate of return that makes the net present value of all cash flows from the investment equal to zero. Higher IRR values indicate better returns on investment. The IRR should be higher than the cost of capital or the required rate of return. A typical benchmark for solar PV projects is an IRR of 6-10% or higher, depending on the risk profile and financing conditions.
ROI	ROI is a financial metric used to evaluate the efficiency or profitability of an investment. It is calculated by dividing the net profit from the investment by the initial cost of the investment. A higher ROI indicates better profitability. A higher ROI indicates better economic viability. For solar PV systems, an ROI of 10-20% is often considered attractive.
LCOE	LCOE is a metric used to assess the cost of generating electricity from a specific source over the lifetime of the system. It represents the per-unit cost of electricity produced and helps compare the cost-effectiveness of different energy generation technologies. The LCOE should be lower than the current electricity prices from conventional sources and competitive with other RE sources. A benchmark figure might be around \$0.03 to \$0.10 per kWh, depending on location and technology.
CapEx	CapEx is the upfront costs associated with installing the PV system. CapEx includes expenses for solar panels, inverters, mounting structures, electrical components, and labour.
OpEx	OpEx are ongoing costs that cover maintenance, monitoring, and insurance. OpEx affects the overall project economics. A lower ratio is preferable, typically less than 20%, indicating efficient operation and maintenance management.
NPV	The NPV calculates the present value of all future cash flows generated by the PV system, taking into account the time value of money. A positive NPV indicates that the system is economically viable. A positive NPV indicates that the projected earnings (in present value terms) exceed the investment costs, thus the project is economically viable
Payback Period	The payback period is the time it takes for the initial investment to be recouped through energy savings. A shorter payback period signifies a more economically viable system. For solar PV systems, a payback period of 5-10 years is generally considered good, although this can vary by region and specific project conditions.

### III. Results and analysis

PV assessment and system performance of two location scenarios, onshore (LPV system) and offshore (LPV system), in North Durban, SA, will be conducted. This section covers all technical aspects of the PV system, ranging from assessing PV potential to determining the performance of a hypothetical 10 MWp installed capacity of PV systems, utilising Solargis and PV\*SOL software applications. It involves a detailed depiction of site locations, PV system setup, and simulations carried out at both site scenarios. The resulting reports will be used to analyse, compare, and discuss solar PV potential and system performance,

taking into consideration factors, such as irradiation, power generation output, performance ratio (PR), and capacity ratio (CR). The data obtained will be exploited for comparative analysis of the two media to establish their both technical and economic feasibilities as shown in in Table 4.

Table 4. Site Characteristics and PV System Configuration

Attribute	Ground-Based Fixed-Mounted (LPV)	Floating PV (FPV)
Site Platform	Large-scale commercial PV system mounted on level terrain. Modules are fixed at an optimal tilt for yearly energy output.	PV modules on floating pontoons, benefiting from water cooling but facing higher soiling and environmental challenges.
System Size	10 MWp	10 MWp
PV Module Type	Polycrystalline silicon (c-Si)	Polycrystalline silicon (c-Si)
Module Orientation	Azimuth: 0° · Tilt: 31°	Azimuth: 0° · Tilt: 10°
Row Spacing	2.5	1.4
Inverter Type	High-efficiency centralized inverter	String inverter
Transformer Type	High-efficiency transformer	Standard transformer
Snow Losses	0%	0%
Soiling Losses	Up to 3.5%	Up to 6.0%
Cabling Losses	DC: 2.0%, DC mismatch: 0.3%, AC: 0.5%	DC: 2.5%, DC mismatch: 3.5%, AC: 2.0%
System Availability	99.5%	98.0%

### III.1. Global irradiance on a plane surface

The values of GHI, DNI, and DIF provide insights into the solar energy resource available at both onshore and offshore locations, which is useful for planning and designing solar energy projects, as well as assessing the potential for solar energy generation in these areas. From the results obtained, as presented in Figure 3, the annual profiles and sums Figure 3(b) of three solar irradiance components measured in kWh/m<sup>2</sup> for both onshore and offshore locations. The GHI measures the total amount of solar radiation received on a horizontal surface at the location throughout the year. For the onshore location, the annual sum of GHI is 1661.2 kWh/m<sup>2</sup>, and for the offshore location is 1680 kWh/m<sup>2</sup>, presented in Figure 3(b).

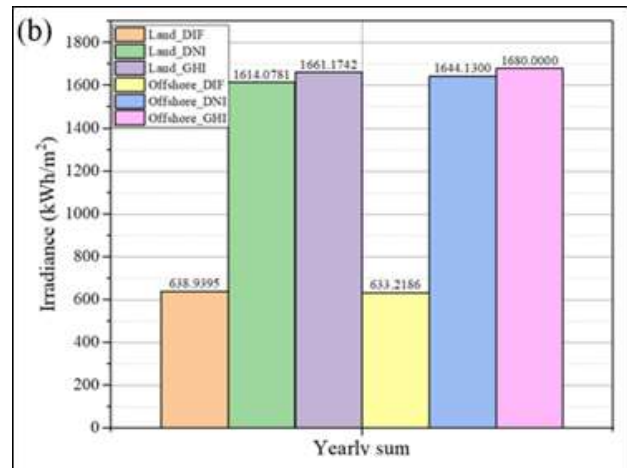
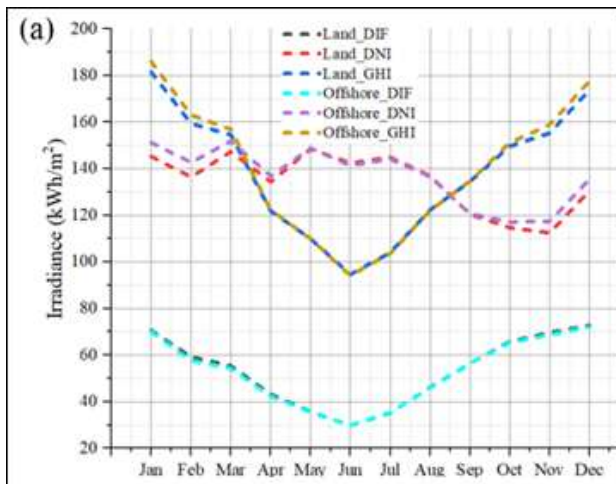


Figure 3. PV potential of Durban North (a) Irradiance profiles across the months; (b) yearly sum irradiance

### III.2. Global Tilt Irradiance (GTI) and total PV energy generated (PVO<sub>UT</sub> total)

The values of GTI and PVO<sub>UT</sub> provide insights into the solar energy potential and actual energy generation of both onshore and offshore locations equipped with PV systems. It indicates the amount of solar energy available for conversion into electricity and the actual electricity output generated by the PV systems installed at these locations. From the data obtained from this study, as presented in Figure 4 (a) and (b):

- i. The GTI measures the total amount of solar radiation received on a surface that is tilted to optimise solar

energy capture throughout the year. For the onshore and offshore locations, the annual sum of GTI is  $1.87 \times 10^3$  kWh/m<sup>2</sup>, and  $1.8 \times 10^3$  kWh/m<sup>2</sup>, respectively.

- ii. The PVOUT<sub>total</sub> represents the total amount of energy generated by a PV system over a year. For the onshore and offshore locations, the annual sum of PVOUT is  $1.5 \times 10^7$  kWh and  $1.3 \times 10^7$  kWh, respectively.

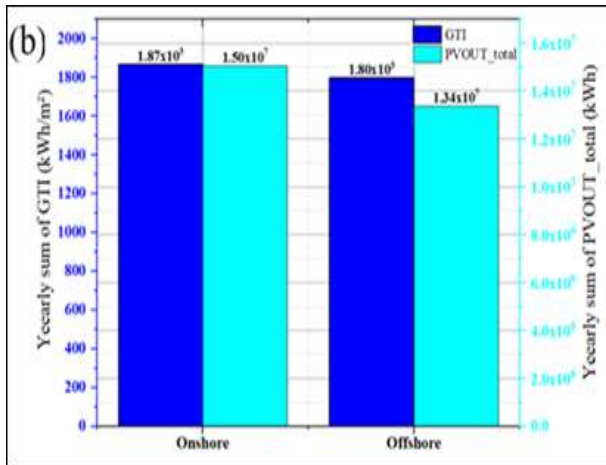
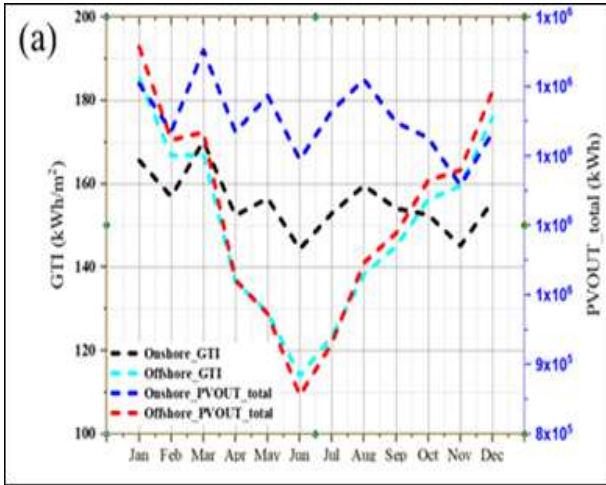


Figure 5. PV system performance (a) yearly sum of GTI and PVOUT total; (b) Profiles of GTI and PVOUT total

### III.3. Performance ratio (PR)

The yearly profiles of PR at monthly average for both onshore and offshore locations are presented in Figure 6(a) while Figure 6(b) depicts the yearly sum of PVOUT specific and average of PR, respectively. The following observations were made:

- i. In Figure 6(a), the highest monthly PR occurred in June for onshore and August for offshore locations. The highest and lowest monthly PVOUT-specific sums were in March and June, respectively, for

onshore, and in January and June, respectively, for offshore, with a significant shift between March and June.

- ii. In Figure 6(b), the yearly PVOUT-specific sum for onshore and offshore sites was 1500 kWh/kWp and 1340 kWh/kWp, respectively, showing an 11% difference. The yearly averages PR for onshore and offshore sites were 80.6% and 74.4%, respectively.

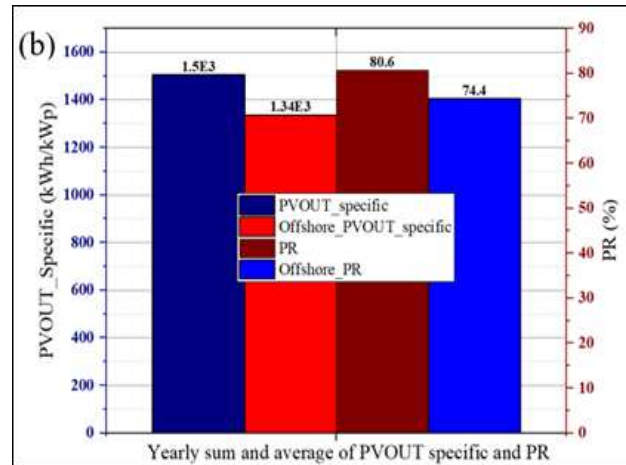
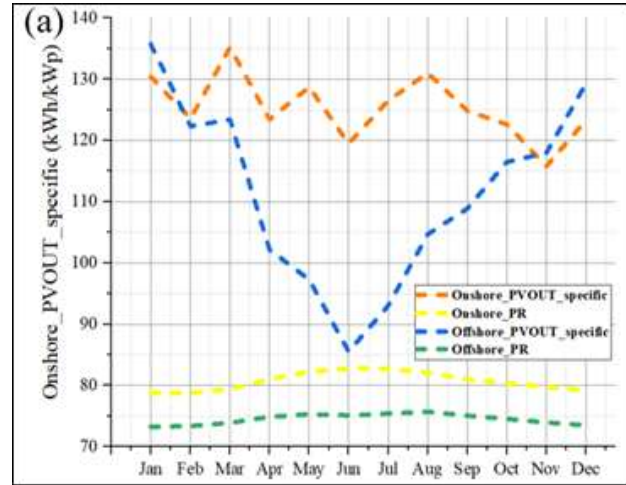


Figure 6. Power generation performance (a) PVOUT specific monthly profile; (b) Yearly sum and average of PVOUT specific and PR, respectively

### III.4. Solar PV system degradation

Degradation losses in onshore and floating photovoltaic (FPV) systems refer to the gradual decline in performance over time due to environmental and operational factors. For onshore systems, common causes include temperature fluctuations, UV exposure, dust accumulation, and mechanical wear, which can reduce module efficiency and energy output. In FPV systems, degradation is influenced by additional factors such as

higher humidity, water-induced corrosion, and wave-induced stress. While FPV systems benefit from lower operating temperatures due to water cooling, they may experience higher soiling rates and material degradation from the aquatic environment. Monitoring and mitigating these losses are crucial to maintaining system efficiency and extending their operational lifespan.

The degradation losses of onshore and FPV systems over 25 years were reported in terms of PVOUT specific, PVOUT total, and PR metrics. The report shows that:

- i. In an LPV system over 25 years, the degradation losses led to a decrease in PVOUT specific by 161.0 kWh/kWp, PVOUT total by  $1.8 \cdot 10^6$  kWh (1.8 GWh) and PR decrease by 5.3%.
- ii. In an FPV system over 25 years, the degradation losses led to a decrease in PVOUT specific by 161.0 kWh/kWp, PVOUT total by  $1.61 \cdot 10^6$  kWh (1.61 GWh) and PR decrease by 9%.

According to the report, the LPV system experienced a higher reduction in total output (1.8 GWh) compared to the offshore system (1.61 GWh). However, the FPV system suffered more significant efficiency losses over the 25 years compared to the onshore system as a larger PR decrease is observed in offshore sites. The FPV system had a higher decrease in PR (9%) compared to the onshore system (5.3%).

### *III.5. Economic Comparison of Onshore and Floating PV Systems*

This study evaluates the economic performance of onshore and floating PV (FPV) systems by analyzing key financial indicators. These metrics underscore the distinctions in profitability and financial viability between the two systems, as detailed in Table 6.

### *III.6. Feasibility Analysis*

An evaluation of technical and economic parameters, as outlined in Tables 5 and 6, highlights that LPV systems generally exhibit superior feasibility compared to FPV systems. Onshore PV installations benefit from greater solar irradiance, higher energy output, and enhanced operational efficiency. Additionally, these systems are simpler to install, maintain, and are more durable over time. Offshore systems, though advantageous under certain conditions, incur higher costs and face operational complexities, which can hinder their feasibility. Consequently, LPV systems are often more dependable and efficient for energy production, reflecting trends observed worldwide. Despite the potential benefits of

FPV systems in addressing land constraints and diversifying the energy mix, their technical challenges and relatively lower performance metrics limit their overall viability. Furthermore, LPV systems require less initial investment, incur lower operating costs, and yield better financial returns.

### *III.7. Prospect of FPV in South Africa*

Although FPV adoption in South Africa is still in its infancy, its potential for growth is significant. With adequate support and promising pilot results, FPV could play a pivotal role in the country's renewable energy (RE) strategy. Key prospects for FPV include:

South Africa's extensive network of dams and reservoirs offers ample opportunities for FPV deployment. Combining FPV with hydropower plants could significantly enhance energy capacity and efficiency. Covering just 3-4% of reservoir surfaces could increase output from the current hydropower capacity of 3,339 MW to approximately 3,439–3,473 MW, optimizing existing infrastructure while avoiding additional land use. FPV systems could foster synergy between energy generation and water resource management by reducing evaporation and improving water sustainability.

Scaling up FPV deployment, guided by feasibility studies and pilot projects, could make substantial contributions to South Africa's RE targets and energy diversification.

Adoption of FPV technology could drive innovation in renewable energy, leading to solutions tailored to the country's geographical and climatic conditions.

Table 5. Onshore and offshore solar PV sites parameters and their significance

Parameters	Onshore result	Offshore result
GTI Global Range: 1200 to 2500 kWh/m <sup>2</sup>	A yearly sum of 1866 kWh/m <sup>2</sup> , indicates a significant amount of solar energy available for conversion by the PV panels. A value of 144.3 kWh/m <sup>2</sup> for the month (June) with the least potential indicates a high solar energy available for conversion by the PV panels.	A yearly sum of 1797 kWh/m <sup>2</sup> , indicates a significant amount of solar energy available for conversion by the PV panels. A value of 113.8 kWh/m <sup>2</sup> for the month (June) with the least potential indicates a high solar energy available for conversion by the PV panels.
PVOUT total For 10 MW acceptable range: systems 10 to 18 GWh annually	With a total output of 15 GWh, it indicates that the LPV system is highly productive and capable of generating a significant amount of electricity annually. Despite June, being the month with the least PV generation, a total output of 1.2 GWh reported is still considerable, indicating the system's capacity to produce electricity even during less favourable periods.	With a total output of 13 GWh, it suggests that the FPV system is capable of generating a substantial amount of electricity annually. Despite June being the month with the least PV generation, the total output of 855 MWh is still considerable, indicating the system's capacity to produce electricity even during less favourable periods
PR Typical global range: 70% to 90%	A yearly average PR of 82.8 indicates that the system is operating efficiently, with relatively low losses due to factors like shading, temperature, and soiling.	A yearly average of PR of 75.1% suggests that the system is operating with moderate efficiency.
TEMP Typical global range: 15°C to 25°C	At 18.5 °C, the temperature is moderate, which is favourable for the performance of the PV system. Higher temperatures might lead to decreased efficiency, so moderate temperatures are generally beneficial.	TEMP average yearly and in June 21.6 °C and 18.9 °C, respectively, are moderate. They are beneficial for the PV system's performance. Higher and very low temperatures lead to efficiency decrease, so moderate temperatures are generally more favourable
WS Typical Global Range: 2 to 6 m/s	A yearly average WS of 3.7 m/s and a June average of 3.1 m/s suggest moderate wind conditions at the onshore site. It provides a lesser cooling effect and requires a less robust structural design and engineering to withstand higher wind loads and dynamic forces compared to the FPV system.	WS's yearly average of 4.63 m/s and June average of 3.9 m/s are relatively higher compared to the onshore site. These values are within a reasonable range and help to maintain optimal operating temperatures for the panels. However, high wind speeds have significant implications for the design, installation, and operation of the PV system. It requires a more robust structural design and engineering to withstand higher wind loads and dynamic forces.
RH Typical global range: 50% to 80%	Annual and June average of RH of 77% and 71%, suggests moderate to high humidity levels at the site, which may not significantly affect solar panel performance.	Annual and June average of RH of 78% and 73%, suggests moderate to high humidity levels at the site, which may not significantly affect solar panel performance.
HDD Higher HDD indicates colder climates, requiring more heating	HDD yearly average of 489 degree days means low to moderate, suggesting mild winters and lower thermal stress from cold	HDD yearly average of 48.8-degree days, suggests a relatively mild climate with limited demand for heating.

Table 6. Onshore and FPV systems financial parameters

	Onshore	Offshore	Global benchmark [51-54]	Remarks on performance
IRR project (%)	4.76	1.87	LPV: 6% to 10% FPV: 4% to 8%	The LPV system has higher IRR values for both the project and equity compared to the offshore system, indicating potentially better returns on investment for stakeholders.
IRR equity (%)	7.15	0.68		
ROI (%)	26.54	3.02	LPV: 20% to 30% FPV: 10% to 20%	The LPV system shows a significantly higher ROI (26.54%) compared to the offshore system (3.03%), suggesting better profitability for the onshore project.
LCOE (USD/kWh)	0.04612	0.05664	LPV: 0.03 to 0.06 USD/kWh FPV: 0.05 to 0.10 USD/kWh	The LPV system has a lower LCOE (0.04612) compared to the offshore system (0.05664), indicating that the onshore project may be more cost-effective in terms of energy production.
CAPEX (USD)	9,000,000	10,620,000	LPV: 800,000 to 1,200,000 USD per MW installed FPV: 1,200,000 to 2,500,000 USD per MW installed	The offshore system's CapEx is \$1,620,000.00 more than the onshore system, which is approximately 18% higher. This means that the onshore system requires less upfront investment.
OPEX (USD/annually)	157,500	176,250	LPV: 10,000 to 20,000 USD per MW annually FPV: 0,000 to 40,000 USD per MW annually	The offshore system's OpEx is \$18,750.00 more than the onshore system, which is about 11.9% higher. It means that the onshore system is more cost-effective to operate on an annual basis.

## IV. Conclusion

South Africa ranks as Africa's largest CO<sub>2</sub> emitter and is among the top global producers of greenhouse gases, largely due to coal-based electricity generation. However, the nation's climatic and hydrological resources provide promising opportunities for expanding FPV systems. Key findings from the study include:

- LPV systems demonstrate global competitiveness with high GTI, substantial energy output, and strong performance ratios (PR). FPV systems also perform well but show room for efficiency improvement, as reflected in their PR.
- FPV technology could significantly enhance South Africa's RE capabilities, addressing power supply needs, mitigating water scarcity, and fostering sustainable development.
- Integrating FPV with other RE sources in hybrid systems could enhance grid stability and operational efficiency.
- Continued research, development, and supportive policies are critical to advancing FPV adoption.

The study concludes that PV systems exhibit commendable performance in both onshore and offshore applications, with average yearly PRs of 80.6% and 74.4%, respectively.

## Declaration

- The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.
- The authors declare that this article has not been published before and is not in the process of being published in any other journal.
- The authors confirmed that the paper was free of plagiarism

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## Reference

- [1] UNEP, "Adaptation Gap Report 2023: Underfinanced. Underprepared," United Nations Environment Programme (UNEP), Nairobi2023. Available: <https://wedocs.unep.org/handle/20.500.11822/43796>
- [2] H. Magidimisha-Chipungu, "Why are floods in South Africa's KwaZulu-Natal so devastating? Urban planning expert explains," The Conversation Africa, Inc., South Africa2024.
- [3] PreventionWeb, "South Africa: Flooding in KwaZulu-Natal and Eastern Cape 2022," United Nation Office for Disaster Risk Reduction (UNDRR), Switzerland2022. Available: <https://www.preventionweb.net/collections/south-africa-flooding-kwazulu-natal-and-eastern-cape-2022>
- [4] IEA, "Total CO<sub>2</sub> emissions from energy," International Energy Agency (IEA), Paris2022. Available: <https://www.iea.org/countries/south-africa/emissions#what-are-the-main-sources-of-co2-emissions-in-south-africa>
- [5] ESKOM, "What is the market share of Eskom in South Africa?," Electricity Supply Commission (ESKOM), South Africa2023. Available: <https://eskomloadsheddingschedule.co.za/what-is-the-market-share-of-eskom-in-south-africa/>
- [6] M. Crippa, D. Guizzardi, M. Banja, E. Solazzo, M. Muntean, E. Schaaf, et al., "CO<sub>2</sub> emissions of all world countries," Publications Office of the European Union, Luxembourg2022. Available: <https://publications.jrc.ec.europa.eu/repository/handle/JRC130363>
- [7] H. Ritchie and M. Roser, "CO<sub>2</sub> Emissions," Our World in Data2020. Available: <https://ourworldindata.org/co2-emissions>
- [8] Statista, "Production-based carbon dioxide (CO<sub>2</sub>) emissions in Africa in 2021 by country," Stasta, Germany2023. Available: <https://www.statista.com/statistics/1268395/production-based-co2-emissions-in-africa-by-country/>
- [9] F. V. Bekun, F. Emir, and S. A. Sarkodie, "Another look at the relationship between energy consumption, carbon dioxide emissions, and economic growth in South Africa," Science of The Total Environment, vol. 655, pp. 759-765, 2019/03/10/ 2019. Available: <https://www.sciencedirect.com/science/article/pii/S004896971834628X>
- [10] G. Cohen, J. T. Jalles, P. Loungani, and R. Marto, "The long-run decoupling of emissions and output: Evidence from the largest emitters," Energy Policy, vol. 118, pp. 58-68, 2018/07/01/ 2018. Available: <https://www.sciencedirect.com/science/article/pii/S0301421518301605>
- [11] I. Tiseo, "CO<sub>2</sub> emissions from fossil fuel and industrial purposes in South Africa 1970-2022," Statista, Germany2023.
- [12] ESI, "Eskom own figures show the power generation crisis is worsening ", ESI Africa, South Africa2023. Available: <https://www.esi-africa.com/industry->

- [sectors/generation/eskoms-own-figures-show-the-power-generation-crisis-is-worsening/](#)
- [13] Enerdata, "South Africa energy report," Enerdata, Grenoble, France2024. Available: [https://www.enerdata.net/estore/country-profiles/south-africa.html?check\\_logged\\_in=1](https://www.enerdata.net/estore/country-profiles/south-africa.html?check_logged_in=1)
- [14] M. A. Destek and A. Sinha, "Renewable, non-renewable energy consumption, economic growth, trade openness and ecological footprint: Evidence from organisation for economic Co-operation and development countries," *Journal of Cleaner Production*, vol. 242, p. 118537, 2020/01/01/ 2020. Available: <https://www.sciencedirect.com/science/article/pii/S0959652619334079>
- [15] M. Sebri and O. Ben-Salha, "On the causal dynamics between economic growth, renewable energy consumption, CO2 emissions and trade openness: Fresh evidence from BRICS countries," *Renewable and Sustainable Energy Reviews*, vol. 39, pp. 14-23, 2014/11/01/ 2014. Available: <https://www.sciencedirect.com/science/article/pii/S1364032114004857>
- [16] I. Hanif, S. M. Faraz Raza, P. Gago-de-Santos, and Q. Abbas, "Fossil fuels, foreign direct investment, and economic growth have triggered CO2 emissions in emerging Asian economies: Some empirical evidence," *Energy*, vol. 171, pp. 493-501, 2019/03/15/ 2019. Available: <https://www.sciencedirect.com/science/article/pii/S0360544219300131>
- [17] F. Belaïd and M. H. Zrelli, "Renewable and non-renewable electricity consumption, environmental degradation and economic development: Evidence from Mediterranean countries," *Energy Policy*, vol. 133, p. 110929, 2019/10/01/ 2019. Available: <https://www.sciencedirect.com/science/article/pii/S0301421519305166>
- [18] A. O. Acheampong, "Economic growth, CO2 emissions and energy consumption: What causes what and where?," *Energy Economics*, vol. 74, pp. 677-692, 2018/08/01/ 2018. Available: <https://www.sciencedirect.com/science/article/pii/S014098831830272X>
- [19] Y. Chen, J. Zhao, Z. Lai, Z. Wang, and H. Xia, "Exploring the effects of economic growth, and renewable and non-renewable energy consumption on China's CO2 emissions: Evidence from a regional panel analysis," *Renewable Energy*, vol. 140, pp. 341-353, 2019/09/01/ 2019. Available: <https://www.sciencedirect.com/science/article/pii/S0960148119303635>
- [20] F. Bilgili, S. P. Nathaniel, S. Kuşkaya, and Y. Kassouri, "Environmental pollution and energy research and development: an Environmental Kuznets Curve model through quantile simulation approach," *Environ Sci Pollut Res Int*, vol. 28, pp. 53712-53727, Oct 2021.
- [21] A. N. Kay Lup, V. Soni, B. Keenan, J. Son, M. R. Taghartapeh, M. M. Morato, et al., "Sustainable energy technologies for the Global South: challenges and solutions toward achieving SDG 7††Electronic supplementary information (ESI) available. See DOI: <https://doi.org/10.1039/d2va00247g>," *Environmental Science Advances*, vol. 2, pp. 570-585, 2023/04/03/ 2023. Available: <https://www.sciencedirect.com/science/article/pii/S275470002300041X>
- [22] IRENA, "IRENASTAT Online Data Query Tool: Renewable energy share of electricity capacity," International Renewable Energy Agency (IRENA), Abu Dhabi2024. Available: [https://pxweb.irena.org/pxweb/en/IRENASTAT/IRENASTAT\\_Power%20Capacity%20and%20Generation/RESHARE\\_2024\\_H1.px/table/tableViewLayout1/](https://pxweb.irena.org/pxweb/en/IRENASTAT/IRENASTAT_Power%20Capacity%20and%20Generation/RESHARE_2024_H1.px/table/tableViewLayout1/)
- [23] IRENA, "Energy Profile: South Africa," International Renewable Energy Agency (IRENA) Abu Dhabi2023. Available: [https://www.irena.org/-/media/Files/IRENA/Agency/Statistics/Statistical\\_Profile\\_s/Africa/South-Africa\\_Africa\\_RE\\_SP.pdf?rev=9851ed405064418e94d8dd8b24893e9](https://www.irena.org/-/media/Files/IRENA/Agency/Statistics/Statistical_Profile_s/Africa/South-Africa_Africa_RE_SP.pdf?rev=9851ed405064418e94d8dd8b24893e9)
- [24] N. Cowling, "Total energy consumption from renewables in South Africa 2005-2021," Statista, Germany2023 Available: <https://www.statista.com/statistics/1214188/south-africa-total-energy-consumption-renewables/>
- [25] N. Cowling, "Total solar energy capacity in South Africa from 2013 to 2023 ", Statista, Germany2024. Available: <https://www.statista.com/statistics/1218115/south-africa-total-solar-energy-capacity/>
- [26] M. Armstrong, "Energy: Africa Leads the World in Solar Power Potential," Statista, Germany2022. Available: <https://www.statista.com/chart/27722/practical-potential-solar-energy-output-by-global-region/>
- [27] L. Moodliar and I. E. Davidson, "Do the Dam Project—Evaluating floating solar photovoltaic and energy storage at Inanda Dam within eThekweni Municipality, South Africa," *Energy Reports*, vol. 9, pp. 1116-1125, 2023/10/01/ 2023. Available: <https://www.sciencedirect.com/science/article/pii/S2352484723009514>
- [28] V. Kumar, K. Lata, R. Bhakar, and P. Mathuria, "Solar Photovoltaic On Water Bodies in Rajasthan," in 2021 9th IEEE International Conference on Power Systems (ICPS), 2021, pp. 1-6.
- [29] V. Ramasamy and R. Margolis, "Floating Photovoltaic System Cost Benchmark: Q1 2021 Installations on Artificial Water Bodies," United States2021. Available: <https://www.osti.gov/biblio/1828287>
- [30] IRENA, "Future of Solar Photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation: paper) ," International Renewable Energy Agency (IRENA), Abu Dhabi, 2019.

- [31] WorldBank, ESMAP, and SERIS, "Where Sun Meets Water: Floating Solar Handbook for Practitioners," World Bank, Washington, DC2019. Available: <https://hdl.handle.net/10986/32804>
- [32] V. Petrica, B. Madalina-Simona, S. Andrei-Victor, A. Dragos-Cristian, B.-N. Dumitru-Doru, and P. Manuela-Cristina, "Assessment of Solar Energy Potential Limits within Solids on Heating-Melting Interval," in Latest Research on Energy Recovery, V. Petrica, Ed., ed Rijeka: IntechOpen, 2022, p. Ch. 4. Available: <https://doi.org/10.5772/intechopen.104847>
- [33] W. S. Ebhota and P. Y. Tabakov, "Evaluation of Critical Solar PV Meteorological and Performance Parameters of a Roof-Mounted Crystalline Solar PV System in Berea, Durban, South Africa," *U.Porto Journal of Engineering*, vol. 8, pp. 20-36, 2022. Available: [https://doi.org/10.24840/2183-6493\\_008.002\\_0003](https://doi.org/10.24840/2183-6493_008.002_0003)
- [34] Y. Ahmed. (2013, 27/12/2023). How to Calculate the Surface Area Required by Solar Panels. Available: <https://www.raymaps.com/index.php/how-to-calculate-the-area-required-by-solar-panels/>
- [35] Inveryer. (2023, 27/12/2023). How to Calculate the Power Generation of a Solar Panel? Available: <https://www.inverter.com/how-to-calculate-the-power-generation-of-a-solar-panel>
- [36] W. S. Ebhota and P. Y. Tabakov, "Assessment of solar PV potential and performance of a household system in Durban North, Durban, South Africa," *Clean Technologies and Environmental Policy*, vol. 24, pp. 1241-1259, 2022/05/01 2022. Available: <https://doi.org/10.1007/s10098-021-02241-6>
- [37] ECOFLOW. (2023, 25/10/2023). The Impact of Temperature on Solar Panel Efficiency: How Heat Affects Your Solar Energy System. Available: <https://blog.ecoflow.com/au/effects-of-temperature-on-solar-panel-efficiency/>
- [38] H. Zondag, D. De Vries, W. Van Helden, R. Van Zolingen, and A. Van Steenhoven, "The yield of different combined PV-thermal collector designs," *Solar energy*, vol. 74, pp. 253-269, 2003.
- [39] S. Krauter and A. Preiss, "Comparison of module temperature measurement methods," in 2009 34th IEEE Photovoltaic Specialists Conference (PVSC), 2009, pp. 000333-000338.
- [40] D. Waterworth and A. Armstrong, "Southerly winds increase the electricity generated by solar photovoltaic systems," *Solar Energy*, vol. 202, pp. 123-135, 2020/05/15/ 2020. Available: <https://www.sciencedirect.com/science/article/pii/S0038092X20303303>
- [41] W. S. Ebhota and P. Y. Tabakov, "Influence of photovoltaic cell technologies and elevated temperature on photovoltaic system performance," *Ain Shams Engineering Journal*, vol. 14, p. 101984, 2023/07/01/ 2023. Available: <https://www.sciencedirect.com/science/article/pii/S2090447922002957>
- [42] Hukseflux, "How to calculate PV performance ratio and performance index," Hukseflux Thermal Sensors B.V. Office, Netherlands2024. Available: <https://www.hukseflux.com/uploads/inline/note-how-to-calculate-pv-power-plant-performance-ratio-and-performance-index-v2404.pdf>
- [43] SMA, "Performance ratio: Quality factor for the PV plant," SMA Solar Technology AG, Niestetal, Germany2024. Available: <https://files.sma.de/downloads/Perfratio-TI-en-11.pdf>
- [44] R. A. T. Khan, M. F. Abbas, A. N. Khan, N. Ahmed, M. A. Qaisrani, and M. Assadi, "Performance assessment and root-cause analysis of a deteriorating On-Grid Industrial PV System for the identification of newly originating power degrading defect," *Energy for Sustainable Development*, vol. 76, p. 101306, 2023/10/01/ 2023. Available: <https://www.sciencedirect.com/science/article/pii/S0973082623001631>
- [45] N. H. Reich, B. Mueller, A. Armbruster, W. G. J. H. M. van Sark, K. Kiefer, and C. Reise, "Performance ratio revisited: is PR > 90% realistic?," *Progress in Photovoltaics: Research and Applications*, vol. 20, pp. 717-726, 2012. Available: <https://onlinelibrary.wiley.com/doi/abs/10.1002/pip.1219>
- [46] N. Reich, B. Mueller, A. Armbruster, V. Sark, K. Kiefer, and C. Reise, "Review of PV performance ratio development." DOI:10.13140/2.1.2138.7204," presented at the World Renewable Energy Forum, WREF 2012, Including World Renewable Energy Congress XII and Colorado Renewable Energy Society (CRES) Annual Conference, Denver, USA, 2012.
- [47] N. M. Pearsall, "1 - Introduction to photovoltaic system performance," in *The Performance of Photovoltaic (PV) Systems*, N. Pearsall, Ed., ed: Woodhead Publishing, 2017, pp. 1-19. Available: <https://www.sciencedirect.com/science/article/pii/B978178242336200001X>
- [48] T. Rahman, A. A. Mansur, M. S. Hossain Lipu, M. S. Rahman, R. H. Ashique, M. A. Houran, et al., "Investigation of Degradation of Solar Photovoltaics: A Review of Aging Factors, Impacts, and Future Directions toward Sustainable Energy Management," *Energies*, vol. 16, p. 3706, 2023. Available: <https://www.mdpi.com/1996-1073/16/9/3706>
- [49] M. W. Ijeoma, H. Chen, M. Carbajales-Dale, and R. O. Yakubu, "Techno-Economic Assessment of the Viability of Commercial Solar PV System in Port Harcourt, Rivers State, Nigeria," *Energies*, vol. 16, p. 6803, 2023. Available: <https://www.mdpi.com/1996-1073/16/19/6803>
- [50] N. Hamisu Umar, B. Bora, C. Banerjee, P. Gupta, and N. Anjum, "Performance and economic viability of the PV system in different climatic zones of Nigeria," *Sustainable Energy Technologies and Assessments*, vol. 43, p. 100987, 2021/02/01/ 2021. Available: <https://www.sciencedirect.com/science/article/pii/S2213138820314156>

- [51] IRENA, "Renewable power generation costs in 2022 ", International Renewable Energy Agency (IRENA), Abu Dhabi.2023. Available: <https://www.irena.org/Publications/2023/Aug/Renewable-power-generation-costs-in-2022>
- [52] IRENA, "Renewable Power Remains Cost-Competitive amid Fossil Fuel Crisis," International Renewable Energy Agency (IRENA), Abu Dhabi.2023. Available: <https://www.irena.org/news/pressreleases/2022/Jul/Renewable-Power-Remains-Cost-Competitive-amid-Fossil-Fuel-Crisis>
- [53] NREL, "2021 ATB Data for Utility-Scale Solar Photovoltaics (PV)," The National Renewable Energy Laboratory (NREL), USA2024. Available: [https://atb.nrel.gov/electricity/2021/commercial\\_pv](https://atb.nrel.gov/electricity/2021/commercial_pv)
- [54] R. Wisser, M. Bolinger, and J. Seel, "Benchmarking Utility-Scale PV Operational Expenses and Project Lifetimes: Results from a Survey of U.S. Solar Industry Professionals," Lawrence Berkeley National Laboratory, USA2020.
- [55] R. M. Almeida, A.-U.-H. Chowdhury, H. Rodrigo, M. Li, and R. J. P. Schmitt, "Offsetting the greenhouse gas footprint of hydropower with floating solar photovoltaics," *Nature Sustainability*, 2024/06/26 2024. Available: <https://doi.org/10.1038/s41893-024-01384-w>
- [56] M. Madeško, V. Helać, A. Fejzić, S. Konjicija, A. Akšamović, and S. Grebović, "Integrating Floating Photovoltaics with Hydroelectricity," *Energies*, vol. 17, p. 2760, 2024. Available: <https://www.mdpi.com/1996-1073/17/11/2760>
- [57] Database.earth. (2024). Hydroplant, South Africa. Available: <https://database.earth/energy/power-plants/hydro-power/south-africa>