



The prospect of floating photovoltaic in clean energy provision and net-zero-emissions

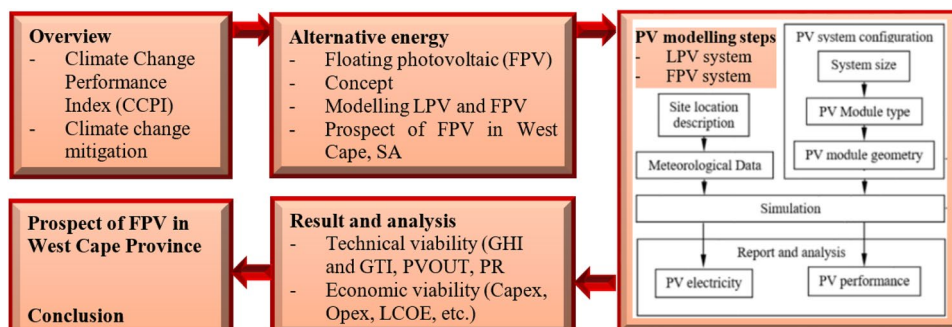
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Abstract

This study emphasizes the critical role of renewable energy in addressing climate change challenges, particularly in reducing greenhouse gas emissions. It highlights the central importance of solar photovoltaic systems. While recognizing South Africa's progress in renewable energy deployment, the study notes that substantial efforts are still needed to meet the country's renewable energy targets. The study's primary aim is to enhance the understanding and deployment of solar photovoltaic systems by critically examining the photovoltaic potential and performance of different sites. To achieve this, two scenarios—land photovoltaic and floating photovoltaic systems—were considered, focusing on hypothetical 10 MWp-installed capacity systems. The results indicate that the 10-MWp land photovoltaic system has a global tilted irradiance of 2184.7 kWh/m², an annual total output of 18 GWh, and an average yearly performance ratio of 81%. The economic parameters for the land photovoltaic system include a capital expenditure of \$9.0 million, an operational expenditure of \$157,500 annually, and a levelised cost of energy of \$0.04089/kWh. In contrast, the 10-MWp floating photovoltaic system reports a Global Tilted Irradiance of 1797 kWh/m², an annual total output of 16 GWh, and a performance ratio of 76%. The economic parameters for the floating photovoltaic system include a capital expenditure of \$10.6 million, an operational expenditure of \$176,250 annually, and a levelised cost of energy of \$0.04936/kWh. Both scenarios' econo-technical parameters fall within acceptable ranges. However, the land photovoltaic system shows better performance, indicating some efficiency loss in the floating photovoltaic system possibly due to harsher offshore conditions. Based on the data from the reports, the study concludes that the econo-technical feasibility of floating photovoltaic in the Western Cape Province of South Africa is high.

Graphical abstract



Keywords South Africa's CO₂ emissions · Land photovoltaic (LPV) · Floating photovoltaic (FPV) systems · Prospect of FPV in West Cape · PV technical parameters · PV financial parameters

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Introduction

The world is facing many challenges due to global climate change, primarily driven by human activities and the emission of greenhouse gases (GHG). Global climate change is caused mainly by human activities that release GHG into the atmosphere, leading to changes in the Earth's climate system. Some of the key causes of global climate change include—the burning of fossil fuels, deforestation, and agricultural activities (Ebhota and Jen 2020). The key challenges associated with global climate change include rising temperatures and an increase in extreme weather events, such as hurricanes, droughts, floods, and wildfires. Others are the impact on biodiversity, food security and agriculture, impact on biodiversity, health risks, and water scarcity. In 2019, worldwide greenhouse gas (GHG) emissions reached 55.3 BtCO₂ equivalent, with CO₂ accounting for 76%, CH₄ for 16%, N₂O for 6%, and F-gases for 2% (EPA 2020). The primary sources of CO₂ emissions were fossil fuel combustion, industrial processes, and land use change. Specifically, in 2019, CO₂ emissions from fossil fuel use amounted to 34.8 billion tonnes, with coal contributing 40%, oil 34%, and natural gas 20% (Ritchie, et al. 2020). In 2021, the global CO₂ emissions totalled around 37.12 BtCO₂, with more than half of these emissions being attributed to the wealthiest 10% of the population. Africa has the lowest per capita emissions globally, averaging 1 tonne of CO₂ per person annually. Comparatively, an average American or Australian emits a similar amount of CO₂ in a month as an individual in Africa does in a year.

In the past, Africa's contribution to global GHG emissions has been relatively modest, estimated at around 3.8% (CDP 2020). However, this share has been increasing over time. According to IEA and EDGAR computation, Africa's carbon emissions represented 4.5% (2511.4 Mt) of the global total in 1970, rising to 6.6% (3021.0 Mt) by 2020. Africa experienced an annual carbon emissions growth rate of 2.1% between 2010 and 2019, notably higher than the global average of 1.2%. This escalation in carbon emissions is closely linked to Africa's economic and social development, which has resulted in alarming rates of energy consumption and CO₂ emissions (Salahuddin et al. 2019; Wang and Dong 2019). Although the continent contributes only a small portion to global emissions, the United Nations Framework Convention on Climate Change (UNFCCC) reported in 2006 that the continent is most vulnerable to the impacts of climate change (UNFCCC 2006). Within Africa, three countries—South Africa (435.9 MtCO₂), Egypt (249.6 MtCO₂), and Algeria (176.2 MtCO₂)—account for over 60% of the continent's carbon emissions (Statista 2023). Due to its heavy reliance on coal for electricity generation, South Africa has

become one of the top 10 GHG emitters globally (Cohen, Jalles, Loungani, and Marto, 2018). By 2022, South Africa had generated 405 MtCO₂ from fossil fuel combustion and industrial processes, indicating a decrease of approximately 3% compared to the previous year (Tiseo 2023). Despite this decrease, the country continues to operate more than twenty coal-fired power plants (Eskom 2024), at a time when the world is shifting towards cleaner, more sustainable sources of energy.

Since the beginning of 2023, the continent has reported several fatalities due to rising temperatures, persistent drought, catastrophic flooding, and destructive cyclones, among other extreme weather events (AfDB 2023b). According to the latest Climate Vulnerability Index 2022, nine of the world's top ten most vulnerable countries—Chad, Central African Republic, Eritrea, Guinea-Bissau, Democratic Republic of Congo, Sudan, Niger, Afghanistan, Liberia, and Somalia are in SSA (AfDB 2023a). The 2022 Climate Change Report from the Intergovernmental Panel on Climate Change on “Impacts, Adaptation, and Vulnerability” also confirmed that most parts of Africa are among the global hotspots of human vulnerability to climate change (UNEP 2023). Several devastating floods and landslides accompanying heavy rainfalls have been reported in KwaZulu-Natal and Eastern Cape provinces, South Africa. Many of South Africa's cities were constructed before the prediction of climate change. The province of KwaZulu-Natal witnessed destructive flooding 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 (Magidimisha-Chipungu 2024). In 2022, over 440 individuals lost their lives, approximately 4,000 homes were destroyed, and the extensive road damage amounted to at least R5.6 billion (PreventionWeb 2022).

The significance of RE in climate change mitigation has been recognised and proven to be effective in addressing the myriads of climate change issues. Renewable energy is essential in this context as it mitigates climate change by reducing GHG emissions, enhancing energy efficiency, diversifying the energy supply, supporting sustainable development, fostering technological innovation, preserving the environment, and driving supportive policies and regulations (Todd and McCauley 2021). The deployment of RE in South Africa has seen significant growth and development over the past decade. The country has recognised the importance of diversifying its energy mix, reducing its dependence on coal, and mitigating climate change impacts (Akinbami et al. 2021). Some of the key aspects of RE deployment in South Africa include solar power—South Africa has significant solar resources, particularly in the Northern Cape. Large-scale solar photovoltaic (PV) and concentrated solar power (CSP) projects have been developed; wind power—coastal regions, especially in the Western and Eastern Cape, have

excellent wind resources. Numerous wind farms have been commissioned under the RE Independent Power Producer Procurement Programme (REIPPPP) (IRENA 2023a). Others are hydropower—while South Africa’s hydropower potential is relatively limited, small-scale hydro projects contribute to the RE mix; and biomass and biogas—there is potential for growth in biomass and biogas projects, particularly in the agricultural sector.

In 2022, solar PV and wind energy represented nearly 90% of all new RE installations and by 2027; solar PV’s installed power capacity is expected to surpass that of coal, becoming the largest in the world (Gibb et al. 2022). Some of the main solar PV projects are Kathu Solar Park (CSP, 100 MW capacity), Jasper Solar Energy Project (96 MW capacity), Redstone Solar Thermal Power (CSP, 100 MW capacity), and Noupoot Wind Farm (80 MW capacity) (GlobalData 2024). While progress has been made in improving power accessibility in South Africa, a significant journey is still ahead before it can successfully reduce its carbon footprint. Again, there is still work to be done to ensure universal access to clean electricity and address the challenges faced by marginalised rural communities in accessing clean, reliable, and affordable energy services. The development of RE in South Africa faces several barriers, such as regulatory and policy challenges, financial constraints, infrastructure and technical issues, economic factors, social and environmental concerns, social and environmental concerns, political and institutional barriers, and market hurdles. Addressing these barriers requires coordinated efforts from the government, private sector, academia, and civil society to create an enabling environment for RE development. This study aims to enhance understanding of solar PV by critically examining its potential and performance and evaluating the role of FPV in South Africa’s energy supply goals. The study covers South Africa’s Climate Change Performance Index (CCPI), climate change mitigation, and PV potential and deployment in sub-Saharan Africa, with a focus on FPV systems. Using computational modelling, two PV system scenarios (LPV and FPV) were analysed, compared, and benchmarked against established

performance parameters. The findings were used to assess the econo-technical feasibility and prospects of FPV in the Western Cape Province of South Africa.

This study is structured as follows: Sects. "Background of the study" and "Methodology" deal with the study’s background and methodology, respectively. Sects. "Computational modelling of LPV and FPV" and "Conclusion" are dedicated to LPV and FPV modelling, and conclusions.

Background of the study

Climate change performance index (CCPI)

The Climate Change Performance Index (CCPI) serves as a tool to foster transparency in both national and international climate policies. Utilising a standardised framework, the CCPI evaluates the climate performance of sixty-three (63) countries and the European Union (EU), collectively responsible for more than 90% of global GHG emissions (CCPI 2024). The assessment focuses on four key categories: GHG emissions (40%), RE (20%), energy use (20%), and climate policy (20%), aiming to gauge climate mitigation efforts comprehensively. The ratings are expressed as percentages, with higher percentages indicating better performance in addressing climate change. Considering the five (5) countries ranked in Africa, as presented in Table 1, Morocco has a CCPI rating of 69.82%, which suggests that it has relatively strong climate policies and initiatives in place compared to the other countries listed. Nigeria follows with a rating of 63.88%, indicating significant efforts in addressing climate change but slightly lower than Morocco. Egypt’s rating is 61.80%, reflecting its commitment to climate action but there is still room for improvement. South Africa’s rating stands at 49.53%, indicating moderate progress in addressing climate change but with notable challenges and areas for improvement. Algeria has the lowest rating among the mentioned countries, with a score of 44.54%, suggesting that it faces significant challenges in addressing climate change and may have fewer initiatives in place compared to the others.

Table 1 Climate Change Performance Index (CCPI) 2024 rating (CCPI 2024)

Countries	GHG (40%)	RE (20%)	Energy use (20%)	Policy (20%)	CCPI (%)	2024 global spot
Morocco	31.18	6.67	16.06	15.91	69.82	9th
Sweden	32.93	15.23	10.42	10.80	69.39	10th
Nigeria	31.51	3.24	17.70	11.43	63.88	17th
Egypt	30.52	3.38	17.18	10.72	61.80	22nd
South Africa	20.77	3.06	15.96	9.74	49.53	45th
China	13.45	9.06	7.14	15.91	45.56	51st
Algeria	22.54	2.01	13.80	6.20	44.54	54th
USA	16.88	3.03	6.69	16.20	42.79	57th
Saudi Arabia	4.85	3.09	6.30	5.09	19.33	67th

Climate change mitigation

To address these global climate change challenges, urgent and coordinated action at local, national, and international levels is required. This involves a range of strategies and actions aimed at reducing the greenhouse gas emissions that contribute to global warming. Some of the key measures are energy efficiency implementation, transition to clean and sustainable energy, carbon capture and storage (CCS), carbon sequestration, and sustainable agriculture and land use (Fawzy et al. 2020). Others are transportation changes, industrial innovations, policy and legislation, behavioural and societal changes, and research and development. These are essentially efforts to reduce greenhouse gas emissions, build resilience to climate impacts, and sustainable development practices that safeguard the future of the planet (Melkonyanet et al. 2024).

In 2023, the total RE capacity in South Africa reached its peak at approximately 10.6 MW, with solar energy comprising about 58% of the total RE capacity (Galal 2024). Several technologies are potential candidates for RE transition and utility applications, including lithium-ion batteries, flow batteries, lead-acid batteries, supercapacitors, flywheels, compressed air energy storage, solar PV, and hydropower (Yang et al. 2011). Renewable energy sources are natural resources that can be converted into clean energy. It is projected that renewables will transform the global power mix by 2027, becoming the largest source of electricity. Currently, hydropower accounts for over 90% of all grid-scale capacity, but it is limited by the availability of suitable locations and high capital costs (Wang et al. 2023).

Methodology

The background study provides an overview of climate change and the Climate Change Performance Index (CCPI) ranking of some countries in SSA using data obtained from secondary sources. These information sources include research articles, government white papers, and reports from reputable international organisations, such as the

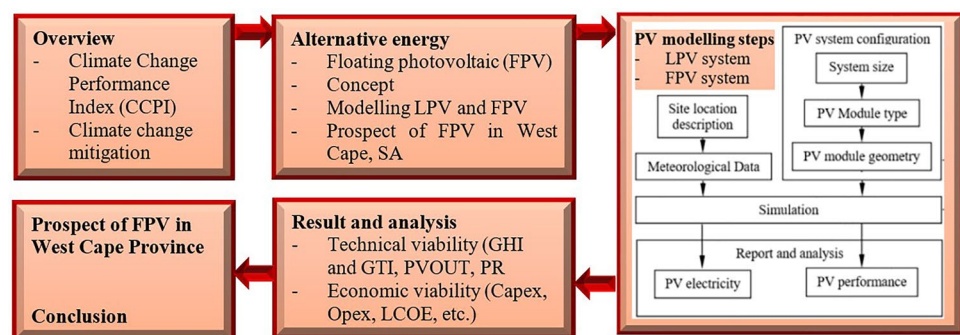
International Energy Agency (IEA), and National Renewable Energy Laboratory (NREL). Others are the Africa Development Bank (AfDB), Global Atlas Data, World Bank Data, CCPI, World Bank, and International Renewable Energy Agency (IRENA). Two scenarios of land photovoltaic (LPV) and floating photovoltaic (FPV) systems were considered to examine PV potential and the performance of hypothetical 10 MW_p-installed capacity PV systems. The solar PV potential will be defined in terms of irradiance parameters while parameters, such as total PV output (PVOUT_{total}), specific PVOUT, and performance ratio (PR) were used to evaluate the PV systems performance. The analysis and the determination of the Econo-technical feasibility and competitiveness of both scenarios were based on the data obtained from the Solargis software application's modelling reports. The study's methodology is depicted in Fig. 1.

Floating/offshore PV system

A Floating Photovoltaic (PV) system, also known as a floating solar farm, is a type of solar power installation where PV panels are mounted on a structure that floats on a body of water, such as a reservoir, lake, or pond. This innovative approach to solar power generation has several unique features and benefits compared to traditional land-based solar farms solar PV panels, mooring systems, floating structures, and electrical components, as shown in Fig. 2. The benefits that follow the deployment of the FPV system are—space efficiency, increased efficiency, reduced evaporation, minimized land use conflicts, and improved water quality.

Most of the current capacity and future growth in the floating photovoltaic (FPV) market is focused in Asia (Aboshosha and Hamad 2024; Panel 2023). This is due to expensive land, scarcity of land, and a strong presence of hydropower production connected to reservoirs driving the deployment of FPV systems. China, India, and South Korea are leading the way in adopting floating PV technology, highlighting their commitment to sustainable energy options. China is the global leader in installed FPV capacity, making up 52% of the total worldwide,

Fig. 1 The study's methodology



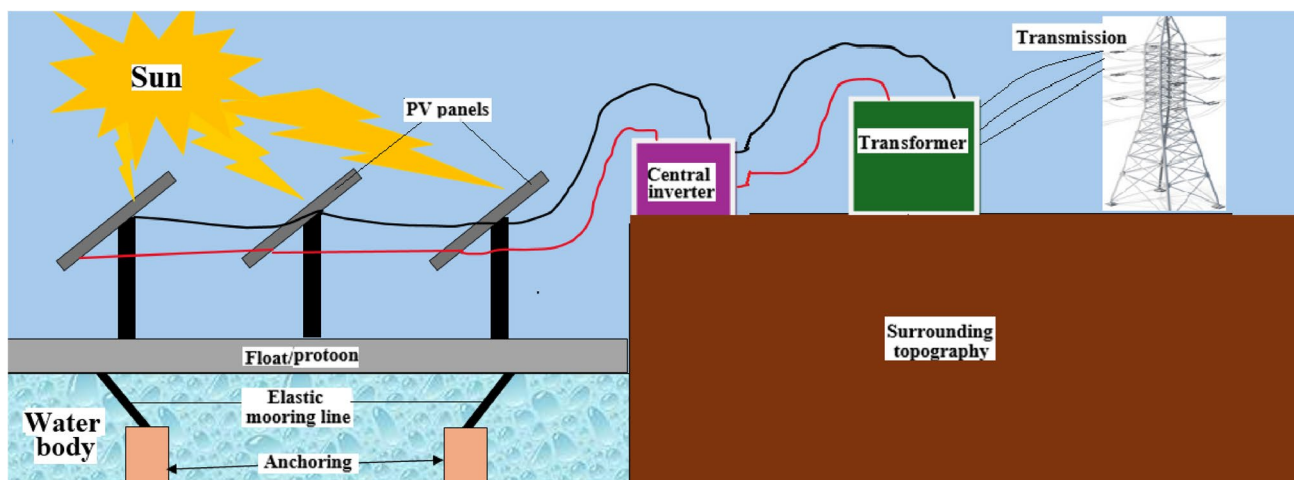


Fig. 2 Illustration of a FPV system and key features

with the Taiwan Region and Japan following behind at 12% and 10% respectively (Ramasamy and Margolis 2021).

In Africa, FPV technology is still at a nascent stage, primarily concentrated on experimental or commercial uses with relatively modest capacities. Numerous organizations and agencies have emphasized Africa's substantial potential for FPV deployment. The German Solar Industry Association has indicated that Africa harbours the largest floating PV generating capacity globally (Deboutte 2021). Furthermore, the Ecofin Agency has reported that the continent boasts more than 100,000 km² of freshwater reservoirs suitable for floating solar installations. Even utilizing just 1% of this area could generate 100 GW of electricity, surpassing the continent's total installed solar capacity in 2022 by eight times (Ecofin 2023). Some countries in Africa, such as South Africa, Kenya, Burundi, and Tunisia, have already established small floating solar power plants (Ecofin 2023).

Differences between solar LPV and solar FPV systems

Solar LPV and Solar FPV systems are two types of solar energy installations that differ primarily in their placement—on land versus on water. Both solar LPV and FPV systems contribute to RE generation, their differences lie in location, efficiency, environmental impact, structural challenges, and costs. The FPV systems offer unique advantages, especially in regions with limited land availability, but they also come with specific technical and environmental considerations. A detailed comparison of the two systems is presented in Table 2.

Floating PV research gaps in Africa

Despite their growing adoption globally, FPV systems in Africa face unique challenges and gaps that need to be addressed. These research gaps can be categorised into environmental impact assessment, technical and design challenges, economic and financial viability, policy and regulatory frameworks, and social acceptance and stakeholder engagement (Gadzanku et al. 2021). Others are energy-water-food nexus, grid integration and energy storage, data availability and monitoring, climate resilience and adaptation. In this work, attention will be given to technical and design challenges and economic and financial viability studies. Details of research gaps in FPV systems as they relate to technical and design challenges and economic and financial viability studies in Africa are presented in Table 3.

These gaps highlight the need for multidisciplinary research that integrates environmental science, engineering, economics, policy, and social sciences to fully realise the potential of floating solar PV systems in Africa.

Photovoltaic potential: Meteorological parameters

Irradiance, including GTI and PV power generation, are closely linked, with irradiance being one of the key parameters influencing the performance of PV systems. There is direct proportionality between GTI and PV power generation: higher GTI values typically result in increased power generation, while lower GTI values lead to reduced power generation. Several factors affect irradiance, directly and indirectly, and in turn, influence PV power generation. Some of the direct influencing parameters are ambient conditions (temperature, wind, dust), geographical location, time of day and year, and lifetime. Others are system efficiency, shading,

Table 2 Comparison between LPV and FPV systems (Jung et al. 2024; Nagababu et al. 2024; SolarEdition 2020)

	LPV	FPV
<i>Location and installation</i>		
Location	Installed on land, such as open fields, rooftops, deserts, or other terrestrial surfaces	Installed on water bodies like lakes, reservoirs, dams, ponds, or even the sea
Installation	Mounted on fixed-tilt racks or solar trackers that are anchored into the ground	Panels are mounted on floating structures anchored to the waterbed using mooring systems
Use of space	Requires significant land space, which can sometimes lead to land-use conflicts, especially in densely populated or agriculturally valuable areas	Utilises water surfaces, conserving valuable land and avoiding competition with agriculture or urban development
<i>Performance and efficiency</i>		
Cooling effect and performance	Panels often get hotter on land, leading to reduced efficiency since photovoltaic cells perform less efficiently at higher temperatures	Water below the panels helps maintain lower operating temperatures, improving overall performance by 5–15% compared to LPV systems
Energy yield	May require more frequent cleaning due to dust and debris, particularly in arid regions	Less dust accumulation on water means lower maintenance for cleaning and potentially higher energy output
<i>Environmental impact</i>		
Effect on ecosystem	May involve clearing vegetation or disturbing soil, which can impact local ecosystems and biodiversity	Minimal impact on terrestrial ecosystems, as they are located on water
Heat island effect	Large land-based solar farms can contribute to local warming, known as the heat island effect	Can reduce evaporation from reservoirs, which is beneficial in water-scarce regions
Biodiversity	Potential impact on local wildlife habitats, especially if located near sensitive ecosystems	Possible impacts on aquatic ecosystems, such as changes in water temperature, reduced light penetration, and effects on local aquatic flora and fauna
<i>Technical and structural challenges</i>		
Structure	Generally, LPV is stable due to firm ground anchoring; and less affected by water-related challenges	Must be designed to withstand water movement, such as waves, currents, and potentially severe weather conditions like storms or typhoons
Maintenance	Accessibility on land makes maintenance tasks like cleaning, panel replacement, or electrical troubleshooting easier	Maintenance can be more challenging due to limited access and safety concerns while working on water
Optimal tilt angles	LPV systems are typically designed to have a fixed or adjustable tilt angle optimized for the geographic location (latitude) to maximize solar exposure throughout the year. In most cases, the optimal tilt angle is close to the site's latitude, adjusted slightly depending on whether the system aims to maximize energy production in the summer or winter	FPV systems often use shallower tilt angles compared to LPV systems, typically ranging from 5° to 15°, due to stability concerns on water. Steeper angles can increase the load on the floating structure and mooring systems, making the system more susceptible to wind and wave forces
<i>Cost considerations</i>		
Initial costs	Generally, LPV systems have lower upfront costs due to simpler installation processes and fewer technical challenges	Installation costs are typically higher due to the need for specialized floating platforms, mooring systems, and waterproof electrical components
Acquisition costs	Land costs can be significant, especially in areas where land is scarce or expensive	This offsets the need for expensive land acquisition, which can be a major cost advantage in regions with high land values
<i>Grid integration</i>		
Grid connection	Often easier to locate near existing grid infrastructure, reducing transmission costs	May require additional infrastructure if located far from existing grid lines or on isolated water bodies
Standard grid connection	Utilises conventional methods for connecting to the grid	FPV systems on hydroelectric dams can directly integrate with existing power infrastructure, potentially enhancing overall grid stability

Table 2 (continued)

	LPV	FPV
<i>Scalability and potential applications</i>		
Scalable	Highly scalable with a wide range of applications, from small rooftop systems to large utility-scale solar farms	Scalability depends on the availability of suitable water bodies and the ability to manage potential environmental impacts
Versatility	Can be adapted to various landscapes, including urban, rural, and desert environments	Can be combined with existing water infrastructure, such as hydropower plants, to create hybrid systems that enhance energy generation efficiency

hours of daylight, solar elevation and azimuth, latitude, altitude, and terrain and obstructions. The indirect influencing parameters include cooling degree-days (CDD) and heating degree-days (HDD). Understanding and optimising these influencing factors are essential for maximising the efficiency and output of PV systems. Meteorological parameters play a crucial role in influencing the potential of both LPV and FPV systems.

Effect of elevated temperature on PV panel performance

Higher temperatures generally lead to lower electrical efficiency, highlighting the potential to enhance PV module performance by implementing cooling technologies. The PV panels typically have an optimal operating temperature of around 25 °C (77°F) (Vig and Kumar 2023). For every degree Celsius above this temperature, the efficiency of silicon-based PV panels generally decreases by about 0.4–0.5% (ECOFLOW 2023). This is due to the increased resistance in the semiconductor materials, which reduces the voltage output. The performance of a PV module is evaluated under standard test conditions (STC) and nominal operating cell temperature (NOCT). Typically, STC conditions are ambient temperature (T_{amb}) of 25 °C (77°F), electrical efficiency (η_o), and an irradiance of 1000 W/m² (Kim and Nam 2019). At STC, the η_o is used as a reference point. The actual operating conditions electrical efficiency (η_{el}) can be calculated using the expressions (Zondag et al. 2003):

$$\eta_{el} = \eta_o(1 - \beta(T - 25)) \tag{1}$$

$$T_m = T_{amb} + (NOCT - 20) \times \frac{G}{800} \tag{2}$$

where T_m is the PV module temperature, β is the temperature coefficient specific to the PV module material.

Effect of wind speed (WS) on PV panel performance

Wind speed and direction play a critical role in maintaining the efficiency of PV panels by providing a cooling effect, but it must be within an optimal range to avoid physical damage. Wind can have both positive and negative effects on PV performance. Moderate wind speeds can help cool PV panels, maintaining their efficiency. However, very high winds can cause physical damage to the panels or supporting structures. According to a study, the mean electricity generated under southerly winds was 20.4–42.9% higher compared to northerly winds (Waterworth and Armstrong 2020). This was attributed to differences in surface cooling capabilities due to the asymmetry of the PV array. The impacts of various WS ranges on PV panel energy generation are presented in Table 4.

Table 3 FPV research gaps in Africa

Category	Description
Technical and design challenges (Gadzanku et al. 2021; Garrod et al. 2024)	Adaptation to local conditions: research on optimising FPV system design to withstand extreme weather conditions common in Africa, such as high temperatures, strong winds, and heavy rainfall Material durability: gaps in understanding the long-term performance and degradation of floating platforms, mooring systems, and PV modules under Africa's climatic conditions Energy output optimisation: Limited studies on the best configurations for maximizing energy yield, including optimal panel tilting, spacing, and orientation for various African latitudes
Economic and financial viability (AEP 2021)	Cost–benefit analysis: Need for comprehensive cost–benefit analyses tailored to African markets, considering factors like installation, maintenance costs, and potential revenue from carbon credits or avoided water evaporation Business models and financing: research on innovative business models, financing mechanisms, and public–private partnerships that can make FPV projects more attractive to investors in Africa

Table 4 Classification of WS ranges WS and their impacts on PV panel and mounting structure

Classification of WS	Range (m/s)	Impact
Low WS (Wai Zhe et al. 2016)	0–1	At very low WSs, the cooling effect is minimal. Consequently, PV panels may experience higher temperatures, reducing their efficiency
Moderate WS (Wai Zhe et al. 2016)	1–5	This range is typically beneficial for PV panel performance. The cooling effect of the wind helps dissipate heat, maintaining lower panel temperatures and enhancing efficiency without causing mechanical stress
Optimal WS (Vasel and Iakovidis 2017)	5–10	In this range, the cooling effect is maximised without posing a risk of damage. PV panels can operate at higher efficiency levels due to effective heat dissipation
High WS (Villan et al. 2024)	10–15	While still providing cooling, high wind speeds begin to introduce the risk of mechanical stress and potential damage to PV panels and their mounting structures. Panels and systems should be designed to withstand these conditions
Very High WS (Gunerhan and Hepbasli 2007)	> 15	At these speeds, the risk of physical damage to PV panels and mounting structures increases significantly. High winds can lead to panel displacement, structural damage, and potential system failures. It is crucial to ensure that the installation is robust enough to handle such conditions

Performance ratio (PR)

According to the latest version of the IEC 61724 standard series, it serves as the primary point of reference that defines essential parameters for evaluating PV systems, such as the performance ratio (PR) and performance index (PI) (Hukseflux 2024). The PR represents the ratio of the actual output of a PV system to the expected output during a specific reporting period, usually based on the system's nameplate rating and is measured in percentage (%). On the other hand, the PI is the ratio of the measured output to the anticipated output over a specific reporting period, using a more complex model of system performance than the performance ratio. Because PR and PI provide similar information, this research study will concentrate exclusively on PR. To calculate the PR, the following variables are required: the solar irradiation values at the PV plant's location, the active area of PV modules (measured in square meters), and the efficiency of the PV modules. The following relation is used to express PR (SMA 2024):

$$PR = \frac{\text{Measured Output}}{\text{Expected Output}} \quad (3)$$

$$= \frac{\text{Actual energy output}}{GTI * A_{\text{panel}} * \eta} \quad (4)$$

where A_{panel} is the surface area of the PV panel measure in meter square (m^2) and η is the PV panel conversion efficiency.

The PR acts as a benchmark for assessing the efficiency of PV plants, providing a location-independent evaluation. Represented as a percentage, it indicates the correlation between the actual and theoretical energy outputs of a PV plant. Essentially, PR represents the portion of energy available for export to the grid once losses, such as thermal and conduction losses, as well as energy consumed for operation, are considered (Williams S. Ebhota and Tabakov 2022). Research indicates that PR values among 100 PV systems in Germany in 2010 ranged from 70 to 90%, with a median

of 84% (Reich et al. 2012). Over the years, the value of PR has been increasing from as low as 50% in the 1980s to over 90% due to advancements in technology. Studies have collectively implied that achieving 100% of the reference yield is unfeasible, with an optimal PR suggested at around 85% (Pearsall 2017; Reich et al. 2012).

Computational modelling of LPV and FPV

In this study, the PV potential and system performance of two location scenarios, onshore (LPV system) and offshore (FPV system), in West Cape, South Africa, will be assessed. This section covers both technical and economic aspects of the PV systems, from evaluating PV potential to determining the performance and financial standpoint of a hypothetical 10 MWp installed capacity using the Solargis software application. It includes a comprehensive description of the site locations, and PV system setups, as presented in Table 5.

Result and analysis

By understanding and optimising these meteorological parameters, the efficiency and output of PV systems can be maximised, leading to better performance and higher energy yields. The yearly profiles of some of these key parameters are presented in Fig. 3a–d.

Effect of meteorological parameters on PV

Operation temperature: The temperatures of the two site scenarios reported in this study, as shown in Fig. 3a and b are below 25 °C and have the same yearly average temperature of 16.2 °C and this supports effective PV generation. In West Cape Province, the temperature is usually higher from December to February and lower from June to August.

Wind speed: From the report obtained in this study, the two site scenarios maintain the same profile trends, as shown in Fig. 3a and b and the annual average of WS of LPV and FPV are 4.2 m/s and 6.1 m/s, respectively. The WS for both LPV and FPV systems fall within the moderate and optimal ranges, which are beneficial for PV panel performance. Specifically, the WS of the LPV system (4.2 m/s), is within the moderate range (1–5 m/s). At this speed, the wind provides a beneficial cooling effect that helps to maintain lower temperatures for the PV panels. The FPV system (6.1 m/s) WS is within the optimal range (5–10 m/s). At this speed, the wind maximises the cooling effect, which significantly improves the efficiency of the PV panels by effectively dissipating heat. This range is particularly advantageous as it provides the most substantial cooling benefits while still being within safe operational limits, therefore ensuring higher energy

generation without posing risks of physical damage to the system.

Impact of length of daylight on PV panel performance

The electrical energy generated by the PV system (PVO_{OUT}) is directly and enormously influenced by both GTI and daylight hours. Longer daylight hours typically result in higher GTI and subsequently, higher PVO_{OUT}, as the panels have more time to generate electricity. From the data obtained from the report, the lowest hours of daylight were observed in June and July while the highest in November and December for both site scenarios. The GTI and PVO_{OUT} total profiles have the same trends as depicted in Fig. 4: Fig. 4a and b are monthly LPV's GTI and PVO_{OUT} total profiles corresponding to daylight hours; Fig. 4c and d are monthly FPV's GTI and PVO_{OUT} total profiles corresponding to daylight hours. The results show that higher GTI and longer daylight hours both positively correlate with increased PVO_{OUT}, as they provide more solar energy for the PV panels to convert into electricity.

Photovoltaic system performance parameters

Quality of PV energy generation

This study presents the annual profiles of PR on a monthly average basis for both LPV and FPV locations in Fig. 5. The following key observations were noted:

- i. Considering the LPV system, the lowest GTI was recorded in June and July due to the relatively short daylight periods, as discussed in Sect. "Effect of meteorological parameters on PV". Interestingly, the highest PR was recorded in July (85.7%), followed closely by June (85.6%), as shown in Fig. 5a. Conversely, the lowest PR was observed in January (78.1%), followed by February and December (78.5%). The study found that the highest PR corresponded to the lowest temperature (11.6 °C), while the lowest PR corresponded to the highest temperature (21.3 °C), as depicted in Fig. 5b.
- ii. Similar trends were observed in FPV systems, where the highest PR (77.1%) and lowest PR (74%) corresponded to the lowest temperature (13.6 °C in August) and the highest temperature (19.2 °C in January), respectively. These results reaffirm the negative impact of elevated temperatures on PV energy generation, consistent with other previous studies (Alavi, Kaaya, De Jong, De Ceuninck, and Daenen, 2024; W. S. Ebhota and Tabakov 2023; Sheikh et al. 2024).

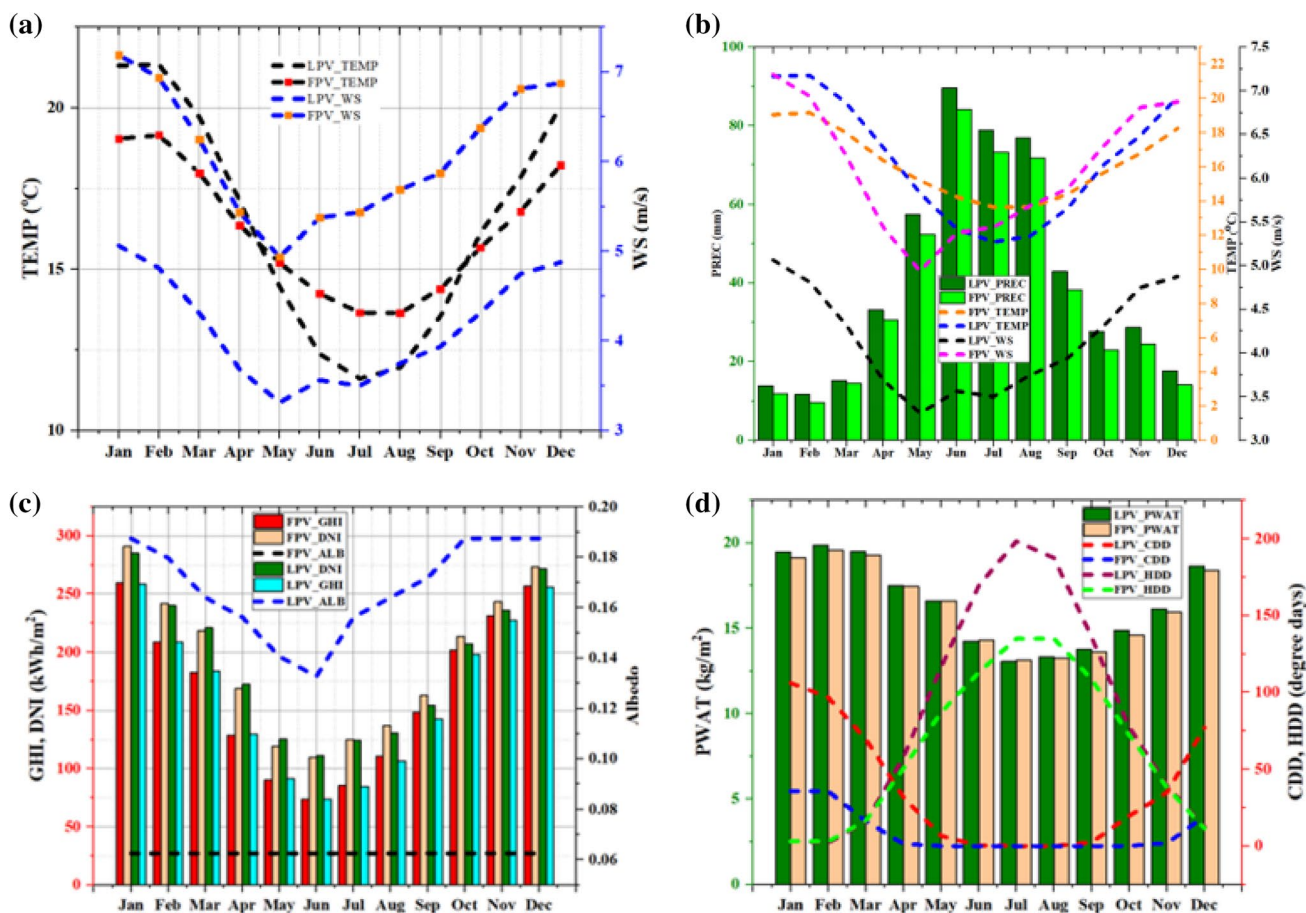


Fig. 3 Irradiance influencing parameters (a) WS and TEMP; (b) PREC, and TEMP (c) Irradiance and Albedo (d) PWAT, CDD, and HDD

For the yearly irradiance and PVOU, the FPV system received higher DHI and GHI, and lower GTI irradiance and generated lesser PVOU compared to LPV, as shown in Fig. 6a. The yearly PVOU total and PR recorded for LPV and FPV are presented in Fig. 6b, with LPV showing 10% and 7% higher PVOU total and quality of generation (PR), respectively.

The higher PVOU and generation quality observed are mainly attributed to the various energy gains, and meteorological and system losses of the two site scenarios, as seen in Fig. 7a. The FPV shows higher system and meteorological losses, and lesser energy gain. Some of the key parameters responsible for the yearly differences between LPV and FPV systems, as shown in Fig. 7b are both meteorological and ambient conditions and electric system losses. The meteorological and ambient parameters include dirt, dust and soiling, angular reflectivity, spectral correction, WS, RH, PREC, and TEMP. The electric system losses are the conversion of solar radiation to DC in the modules and electrical losses due to inter-row shading. Others are power tolerance of PV modules, mismatch and cabling in DC section inverters (DC/AC) conversion, and transformer and AC cabling losses.

Financial parameters of PV systems

In this study, a comparative analysis of LPV and FPV systems was conducted using financial parameters data. These parameters underscore the potential differences in financial performance and profitability between the LPV and FPV systems, as detailed in Table 6.

Feasibility analysis: technical and economic viability

Based on the technical and economic parameters presented in Sect. "Financial parameters of PV systems" and Table 6, LPV systems generally demonstrate higher viability compared to FPV systems. They receive more solar GTI, produce more energy, and operate with higher efficiency. Technically, LPV systems are easier to install, and maintain, and tend to be more durable. Offshore systems, while beneficial in specific scenarios, face higher costs and challenging operational conditions, affecting their overall feasibility. These factors make LPV systems more reliable and effective for energy production, aligning with the typical advantages observed in LPV deployments globally. The FPV systems,

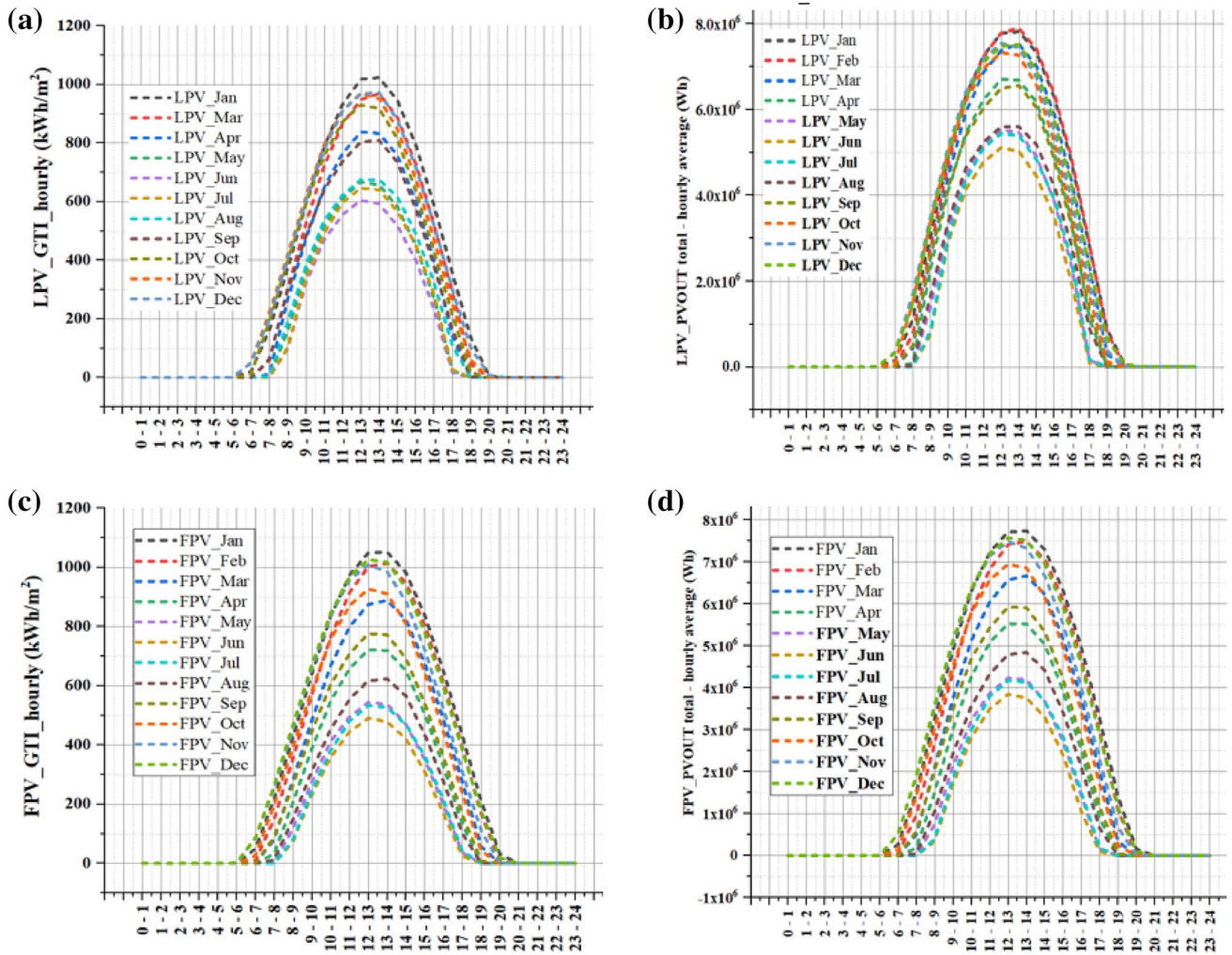


Fig. 4 Daylight impact on (a) LPV GTI; b LPV PVOUT total; c FPV GTI; d FPV PVOUT total

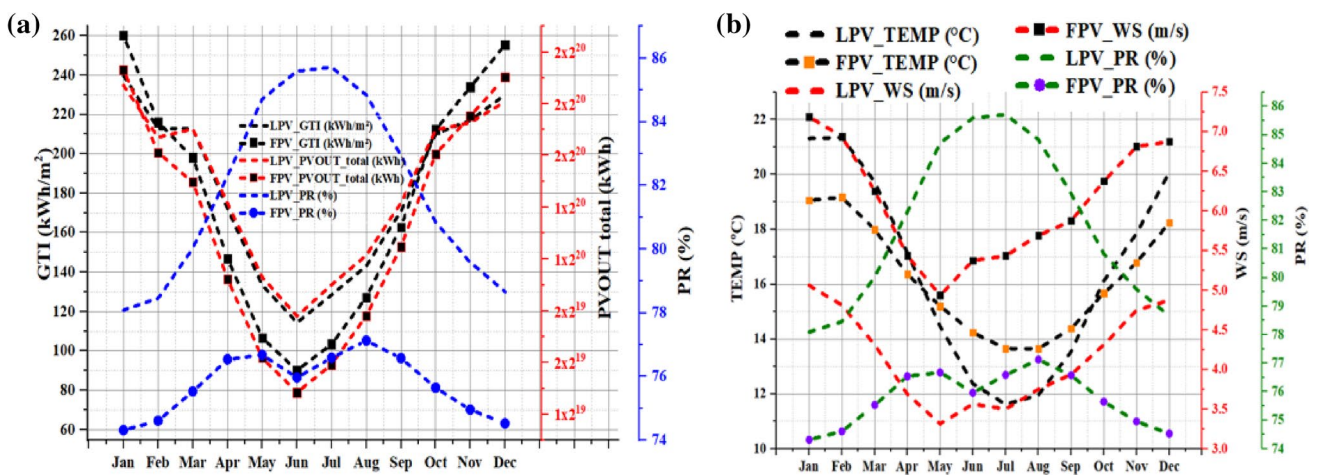


Fig. 5 Profiles of key meteorological and PV performance parameters (a) GTI, PVOUT total, and PR; b TEMP, WS, and PR

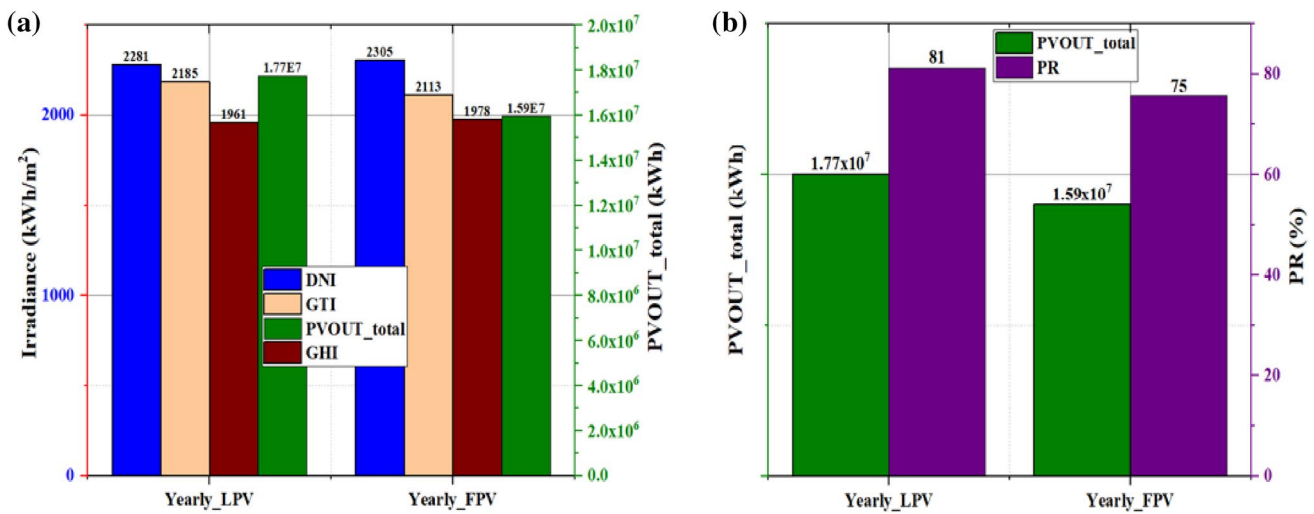


Fig. 6 PV system performance parameters (a) yearly irradiance and PVOUT; b yearly sum of PVOUT total and yearly average of PR

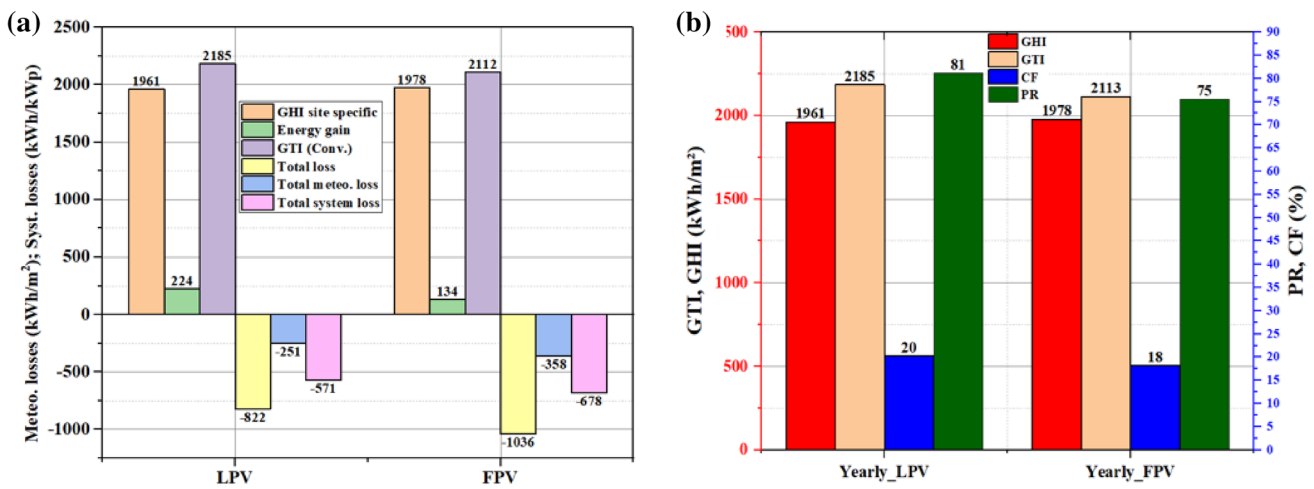


Fig. 7 Energy conversion and losses (a) irradiance and system losses; b irradiance and generation quality

though beneficial in contexts like land space constraints and integration with other energy sources; generally, face more technical challenges and lower performance metrics, impacting their overall technical viability. Interestingly, both LPV and FPV systems meet the current benchmarks of PV potential and system performance parameters, based on the data obtained in this study.

The prospect of FPV in Cape Town, South Africa

While the deployment of FPV in South Africa is currently in its early stages, there is significant interest and potential for growth. With appropriate support and successful pilot outcomes, coupled with the presence of the Palmiet Pumped Storage Scheme (PPSS) for hydroelectricity with

a capacity of 400 MW in the Western Cape Province, FPV could become a crucial component of Cape Town’s RE landscape. The benefits of adopting FPV on such a large scale include:

- i. *Utilisation of existing infrastructure:* PPSS has dams and water reservoirs that can be used for FPV installations, offering significant potential for expanding this technology.
- ii. *The synergy between water and energy resources:* FPV systems are attractive for Cape Town due to the synergy between water and energy resources. Deploying FPV on PPSS water bodies allows the province to generate more clean energy while reducing water evaporation and improving water management.

Table 6 LPV and FPV systems financial parameters

Financial parameters	LPV	FPV	Global benchmark (IRENA 2023b, 2023c; NREL 2024; SolarPower 2024; Wiser et al. 2020)	Remarks on performance
IRR project (%)	6.76	3.69	LPV: 6% to 10%	The LPV system demonstrates higher IRR values for both the project and equity compared to the FPV system, suggesting potentially superior returns on investment for stakeholders. However, the FPV meets the benchmark
IRR equity (%)	12.94	4.54	FPV: 4% to 8%	
ROI (%)	42.70	18.22	LPV: 20% to 30% FPV: 10% to 20%	The LPV system exhibits a significantly higher ROI at 42.70% compared to 18.22% for the FPV system, indicating greater profitability for the onshore project. The 18.22% of FPV's meets the ROI benchmark
LCOE (USD/kWh) (IRENA 2019)	0.04089	0.04936	LPV: 0.03 to 0.06 USD/kWh FPV: 0.05 to 0.10 USD/kWh	Both PV systems indicate cost-effectiveness with the LPV system having a lower LCOE (0.04089 USD/kWh) compared to the FPV system (0.04936 USD/kWh). The LCOE of both systems meets the benchmark
CAPEX (USD) (IRENA 2019)	90,0000MWp	1,062,000 MWp	LPV: 800,000 to 1,200,000 USD per MW installed FPV: 1,200,000 to 2,500,000 USD per MW installed	Although the FPV system is \$1,000.00 more than the LPV system in the CapEx per MW, the two system's scenarios are within the acceptable range in the context of economic feasibility. The LPV system requires a lower upfront investment, as the CAPEX is lower by 18%
OPEX (USD/annually)	15,750	17,625	LPV: 10,000 to 20,000 USD per MW annually FPV: 0,000 to 40,000 USD per MW annually	The annual OPEX of 15,750 USD/MW and 17,625 USD/MW for LPV and FPV systems are within the benchmark range. This means that FPV is about 11.9% higher, making the LPV system more cost-effective to operate on an annual basis

Contribution to RE targets:

- iii. Large-scale FPV projects could contribute to the Western Cape's RE targets and diversify the energy mix.
- iv. *Innovation in RE technologies*: The adoption of FPV could spur innovation in RE technologies and solutions tailored to the Western Cape's unique geographic and climatic conditions.

Conclusion

South Africa is the highest producer of CO₂ in Africa and one of the top 10 GHG emitters globally, primarily due to its reliance on coal for electricity. The unique climate and water resources present opportunities for the expansion of FPV systems. The case study conducted revealed that: the LPV system performs exceptionally well, with

high GTI, substantial total PV output, and an excellent PR, making it competitive on a global scale. The FPV system also performs adequately, with good GTI and reasonable PV output, although the PR indicates room for improvement in efficiency. Both systems meet global standards, with LPV systems showing better overall performance; the Western Cape Province can leverage FPV technology to contribute to its RE goals, increase clean power supply, mitigate water scarcity issues, and promote sustainable development; FPV has the potential to combine with hydroelectric systems and other RE sources in hybrid setups, such as the Palmiet Pumped Storage Scheme (PPSS) in the Western Cape Province, to enhance grid stability and efficiency; and continued research and development, along with supportive policy frameworks, are crucial for the broader adoption of FPV technology in the country. This study concludes that PV systems demonstrate satisfactory performance at both LPV and FPV locations, with yearly average PRs of 80.6% and 75%, respectively.

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Data availability Enquiries about data availability should be directed to the authors.

Declarations

Conflict of interest The authors have not disclosed any competing interests.

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