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Article

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Posted Date: November 2nd, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11161572/v1

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Additional Declarations: No competing interests reported.

Climate-Driven Performance Assessment and Loss Mechanisms of Utility-Scale Photovoltaic Systems

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Abstract: Saudi Arabia possesses exceptionally high levels of solar irradiance, providing substantial potential for utility-scale photovoltaic (PV) deployment. However, the conversion of this solar resource into electricity is strongly influenced by site-specific climatic and environmental conditions, particularly elevated ambient temperatures, airborne dust and soiling, and coastal atmospheric conditions. This study presents a climate-driven comparative assessment of utility-scale PV systems across three representative climatic regions of Saudi Arabia: Qassim, representing an inland desert climate; Makkah, representing a hot-arid climate; and Jazan, representing a hot and humid coastal climate. A hybrid assessment framework is developed by integrating long-term satellite- and meteorological-data-derived climatic inputs from NASA POWER, Solargis, and Meteonorm with detailed PVsyst simulations based on representative utility-scale PV system configurations. Key performance measures, such as specific PV yield, performance ratio (PR), temperature-related losses, and soiling losses, are used to compare the systems. The findings show that increasing solar irradiation does not always result in proportionately higher PV energy generation since environmental losses and high module operating temperatures might significantly outweigh the advantages of the available solar resource. The annual specific PV yield varies from roughly 1650 to 2050 kWh/kWp throughout the locations under investigation, and the corresponding PR varies from 0.76 to 0.84, indicating the impact of site-specific loss mechanisms and climatic circumstances. Instead of depending just on solar-resource intensity, the comparison results

emphasize the significance of including temperature-dependent module performance and environmental loss processes in PV yield evaluations. The work highlights the necessity of climate-aware optimization of PV deployment in high-irradiance desert and coastal locations and offers climate-specific insights for utility-scale PV system design and performance prediction.

Keywords: Utility-scale photovoltaic systems; performance ratio; high-GHI desert climate; thermal losses; PV performance assessment; Saudi Arabia.

1. Introduction

The rapid global expansion of utility-scale photovoltaic (PV) deployment is driven by declining technology costs, ambitious decarbonization targets, and the need to diversify energy portfolios. Among regions with the highest solar resource potential, the Middle East—and Saudi Arabia in particular—stands out due to its exceptionally high global horizontal irradiance (GHI) and vast available land. These characteristics position Saudi Arabia as a key candidate for large-scale PV deployment and have motivated major national renewable energy initiatives. Despite this strong potential, high-GHI desert environments present significant operational challenges. Elevated ambient temperatures, frequent dust events, and coastal humidity can adversely affect PV module efficiency, inverter performance, and overall system yield. In such climates, temperature-induced efficiency losses and inverter thermal derating may offset part of the gains associated with high irradiance. In addition, soiling accumulation can introduce substantial optical losses, particularly in dusty and humid regions.

Previous studies have investigated PV performance under various climatic conditions, including arid, Mediterranean, and temperate regions. However, most existing work focuses on single-site analyses or small-scale systems, with limited emphasis on comparative evaluations of utility-scale PV performance across multiple climatic zones within the same region. Consequently, there remains a need for systematic, multi-site assessments that quantify

how variations in irradiance, temperature, and environmental conditions translate into differences in key performance indicators such as performance ratio (PR) and specific yield.

Saudi Arabia provides a unique natural laboratory for such analysis, encompassing diverse climatic regimes within relatively short geographic distances. Inland regions such as Qassim are characterized by hot, dry desert conditions with very high GHI and large temperature variations. In contrast, Makkah represents a hot arid environment with localized climatic effects, while coastal regions near Jazan are influenced by maritime air masses, higher humidity, and more frequent cloud formation. Evaluating PV performance across these contrasting environments enables a deeper understanding of climate-dependent system behavior.

In this study, a climate-driven performance assessment of utility-scale PV systems is conducted across three representative sites in Saudi Arabia. A hybrid approach is adopted, integrating satellite-based solar and meteorological datasets (NASA POWER, Solargis, and Meteonorm) with detailed PVsyst simulations and realistic system configurations derived from bill of materials (BOM) and inverter specifications.

The main contributions of this work are as follows:

(1) A comparative multi-site evaluation of utility-scale PV performance across distinct desert climatic conditions in Saudi Arabia;

(2) Quantification of the combined impacts of temperature, solar irradiance, and environmental factors on system yield and performance ratio;

(3) Identification of dominant loss mechanisms, including thermal and soiling-related losses, across inland, hot arid, and coastal environments;

(4) Development of climate-aware insights to support improved PV system design, performance prediction, and investment decision-making in high-GHI regions; and

(5) Demonstration that high irradiance alone is not a sufficient predictor of PV performance in desert environments due to temperature-driven efficiency degradation.

These findings contribute to more accurate yield estimation, improved system design, and reduced uncertainty in techno-economic assessment of utility-scale PV projects in desert climates.

2. Literature Review

2.1 Performance Assessment of Utility-Scale PV Systems

Recent studies have extensively investigated the operational performance of utility-scale photovoltaic (PV) plants using key indicators such as performance ratio (PR), specific yield, and capacity factor. These indicators provide a standardized framework for comparing PV performance across different locations and system configurations. Several authors have reported PR values typically ranging between 0.75 and 0.85 for large-scale PV installations operating under favorable climatic conditions, depending on system design, maintenance practices, and environmental factors.

In recent years, increasing attention has been paid to the gap between predicted and actual energy yield in utility-scale PV plants. Studies have highlighted that uncertainties in solar resource assessment, temperature modelling, and loss assumptions can lead to overestimation of annual energy production if not properly accounted for. As a result, performance evaluation studies based on measured or high-quality simulated data have become an essential tool for improving the reliability of yield prediction and reducing investment risk.

2.2 PV Performance in Hot and High-GHI Desert Climates

High solar irradiance regions, particularly those characterized by hot desert climates, present both opportunities and challenges for PV deployment. On one hand, elevated global horizontal irradiance (GHI) levels can significantly increase potential energy generation. On the other

hand, high ambient temperatures lead to a reduction in PV module efficiency due to negative temperature coefficients, as well as thermal derating of inverters during peak operating conditions.

Several recent studies conducted in arid and semi-arid regions have demonstrated that temperature-related losses can account for a substantial portion of total system losses, sometimes exceeding 10% on an annual basis. These losses are often more pronounced during summer months when both irradiance and temperature reach their maximum values. Consequently, net gain from high GHI may be partially offset by thermal effects if system design and cooling strategies are not optimized.

2.3 Environmental Effects: Dust, Soiling, and Humidity

Dust accumulation and soiling are recognized as critical factors affecting PV performance in desert and semi-desert environments. Multiple studies have reported soiling losses ranging from a few percent to more than 20% per year, depending on dust characteristics, cleaning frequency, and local meteorological conditions. In coastal regions, the combined effect of dust and high humidity can further exacerbate optical losses due to cementation and increased adhesion of particles to module surfaces.

Recent research has emphasized the importance of site-specific soiling assessment rather than adopting generic loss assumptions. Seasonal variations, wind patterns, and proximity to urban or industrial areas have been shown to influence soiling rates significantly. Therefore, comparative studies that account for different environmental conditions within the same country can provide valuable insights for optimizing cleaning strategies and maintenance planning.

2.4 PV Performance Modelling and Simulation Tools

Simulation tools such as PVsyst, PVGIS, and the System Advisor Model (SAM) are widely used for predicting PV system performance and evaluating design options. Among these tools,

PVsyst has gained popularity in utility-scale applications due to its detailed loss modelling capabilities and extensive component databases. Recent validation studies have demonstrated that PVsyst can provide reasonably accurate predictions when high-quality climatic inputs and realistic system parameters are used.

However, several authors have pointed out that the accuracy of simulation results is highly dependent on the quality of input data, especially solar irradiance, and temperature profiles. Satellite-based datasets, including those provided by NASA, Solargis, and Meteonorm, have been widely adopted in regions where long-term ground measurements are scarce. Hybrid approaches that combine satellite data with site-specific system information have therefore been recommended to improve the robustness of performance assessments.

2.5 PV Performance Studies in the Middle East and North Africa (MENA) Region The Middle East and North Africa (MENA) regions have attracted growing research interest due to its high solar resource potential and ambitious renewable energy targets. Several studies have investigated PV performance in countries such as the United Arab Emirates, Egypt, and Morocco, highlighting the strong influence of climatic and environmental conditions on system yield and reliability.

Despite Saudi Arabia's leading role in large-scale PV deployment, relatively few peer reviewed studies have provided detailed, comparative performance assessments of utility-scale PV plants across multiple climatic zones within the country. Most existing works focus on single-site analyses or small-scale systems, leaving a gap in the literature regarding how inland desert, hot arid, and coastal humid environments jointly influence PV performance at the utility scale.

2.6 Research Gap and Contribution of This Study

Based on the reviewed literature, it is evident that while substantial progress has been made in understanding PV performance in hot and arid regions, there remains a lack of comprehensive multi-site evaluations for utility-scale PV plants operating under the diverse climatic conditions

of Saudi Arabia. In particular, studies that combine high-GHI desert environments with coastal humid regions using a consistent modelling framework are still scarce.

This study addresses this gap by presenting a comparative performance evaluation of utility scale PV systems across three representative climatic regions in Saudi Arabia, using a hybrid data approach that integrates satellite-based climatic datasets with detailed PVsyst simulations and realistic system specifications. The findings aim to contribute to more accurate performance prediction, improved system design, and informed decision-making for largescale PV deployment in high-GHI desert climates.

3. Methodology

3.1 Study Sites and Climatic Data

Three representative locations in Saudi Arabia are selected to capture the diversity of climatic conditions relevant to utility-scale photovoltaic deployment: Qassim (inland desert), Makkah (hot arid), and Jazan (coastal humid), as illustrated in Fig.1. These sites represent distinct climatic regimes that are highly relevant for evaluating PV system performance under high GHI desert environments.

Long-term solar and meteorological data, including global horizontal irradiance (GHI), direct normal irradiance (DNI), diffuse horizontal irradiance (DHI), ambient temperature, wind speed, and relative humidity, are obtained from satellite-based databases such as NASA POWER, Solargis, and Meteonorm. These datasets provide consistent long-term climatic profiles and are widely employed in PV performance assessment studies, particularly in regions where high-quality ground-based measurements are limited.

The use of satellite-derived solar resource datasets is well supported in the literature, as they enable reliable characterization of spatial variability and uncertainty in irradiance estimation across large geographic areas [29].



Figure 1. Geographic location of the investigated utility-scale PV plant sites in Saudi Arabia, representing inland desert (Qassim), hot arid (Makkah), and coastal humid (Jazan) climatic conditions.

3.2 PV System Configuration and Modelling

A reference utility-scale PV plant is modelled for each site using the PVsyst simulation software. The system configuration is based on realistic bill of materials (BOM) and inverter specifications representative of large-scale PV projects in Saudi Arabia. To ensure fair comparison across locations, the same nominal DC capacity and system layout are assumed for all sites, while climatic inputs vary according to local conditions.

Key system parameters include PV module technology, DC/AC ratio, inverter efficiency and derating characteristics, fixed tilt mounting structure, and electrical losses. Soiling losses are introduced using site-specific assumptions reflecting desert and coastal environmental conditions.

3.3 Performance Indicators

The performance of the PV systems is evaluated using standard performance indicators widely adopted in the literature.

3.3.1 Specific Yield

The specific yield is defined as the annual energy production normalized by the installed DC capacity:

$$Y_f = \frac{E_{AC}}{P_{Dc}}$$

where,

Y_f is the specific yield (kWh/kWp/year)

E_{AC} is the annual AC energy output (kWh)

P_{Dc} is the installed DC capacity (kWp)

3.3.2 Performance Ratio (PR)

The performance ratio represents the overall quality of the PV system by comparing the actual energy output to the theoretical energy output under standard conditions:

$$PR = \frac{Y_f}{Y_r}$$

where,

Y_r is the reference yield, defined as:

$$Y_r = \frac{H_{POA}}{G_{STC}}$$

Here,

H_{POA} is the annual in plane irradiance (kWh/m^2)

G_{STC} is the reference irradiance at standard test condition (1000 W/m^2)

3.3.3 Capacity Factor

The capacity factor (CF) is calculated as:

$$CF = \frac{E_{AC}}{\times 8760} P_{AC}$$

Where, P_{AC} is the rated AC power of the plant (kW).

3.4 Temperature-Related Losses

The impact of temperature on PV module performance is evaluated using the module temperature coefficient. The relative power loss due to temperature can be approximated by:

$$\Delta P_T = (T_{STC} - T_{cell}\gamma)$$

where,

γ is the temperature coefficient of power (% / C^o)

T_{cell} is the PV cell temperature (C^o)

T_{STC} is the reference temperature at STC (25 C^o)

Cell temperature is estimated using standard empirical models implemented in PVsyst, which account for ambient temperature, irradiance, and wind speed.

3.5 Loss Analysis

Total system losses are categorized into thermal losses, soiling losses, inverter losses, clipping losses, and electrical losses. PVsyst loss diagrams are used to quantify the contribution of each loss mechanism to the overall reduction in energy yield. Comparative analysis across the three sites enables identification of the dominant loss factors associated with each climatic condition.

3.6 Uncertainty and Validation Analysis

The accuracy of PV performance prediction in desert environments is influenced by uncertainties associated with solar resource estimation, temperature modeling, and environmental loss assumptions. In this study, uncertainty is minimized through the use of

multiple long-term satellite-based climatic databases, including NASA POWER, Solargis, and Meteonorm, combined with validated PVsyst simulation models.

To improve result robustness, realistic system parameters, inverter specifications, and climate-dependent loss assumptions were adopted consistently across all investigated sites. The simulated performance trends obtained in this work are also consistent with previously reported findings in the literature regarding thermal degradation and soiling impacts on PV systems operating in hot and arid climates.

Although the study primarily relies on simulation-based assessment, the adopted methodology provides a reliable comparative framework for evaluating utility-scale PV performance under diverse climatic conditions. Future work should incorporate long-term operational SCADA data and field measurements to further validate the predicted performance trends and degradation behavior.

4. Results

4.1 Solar Resource and Climatic Conditions

The analysis of the long-term climatic datasets reveals clear differences in solar resource availability and environmental conditions among the three selected sites. The inland desert site in Qassim exhibits the highest annual global horizontal irradiance (GHI), reflecting its dry climate and low cloud cover throughout most of the year. In contrast, the Makkah site shows slightly lower annual GHI values, influenced by its geographical setting and seasonal atmospheric conditions. The coastal site near Jazan records comparatively lower GHI levels due to higher humidity and more frequent cloud formation associated with maritime air masses.

Ambient temperature profiles further highlight significant variability between the sites. Qassim and Makkah experience prolonged periods of high ambient temperatures, particularly during the summer months, while Jazan exhibits relatively moderated temperature fluctuations but consistently higher humidity levels. These climatic differences are expected to play a crucial

role in determining PV system performance and loss mechanisms across the studied locations. The pronounced differences in solar resource availability and ambient temperature across the investigated sites are illustrated in Fig. 2.

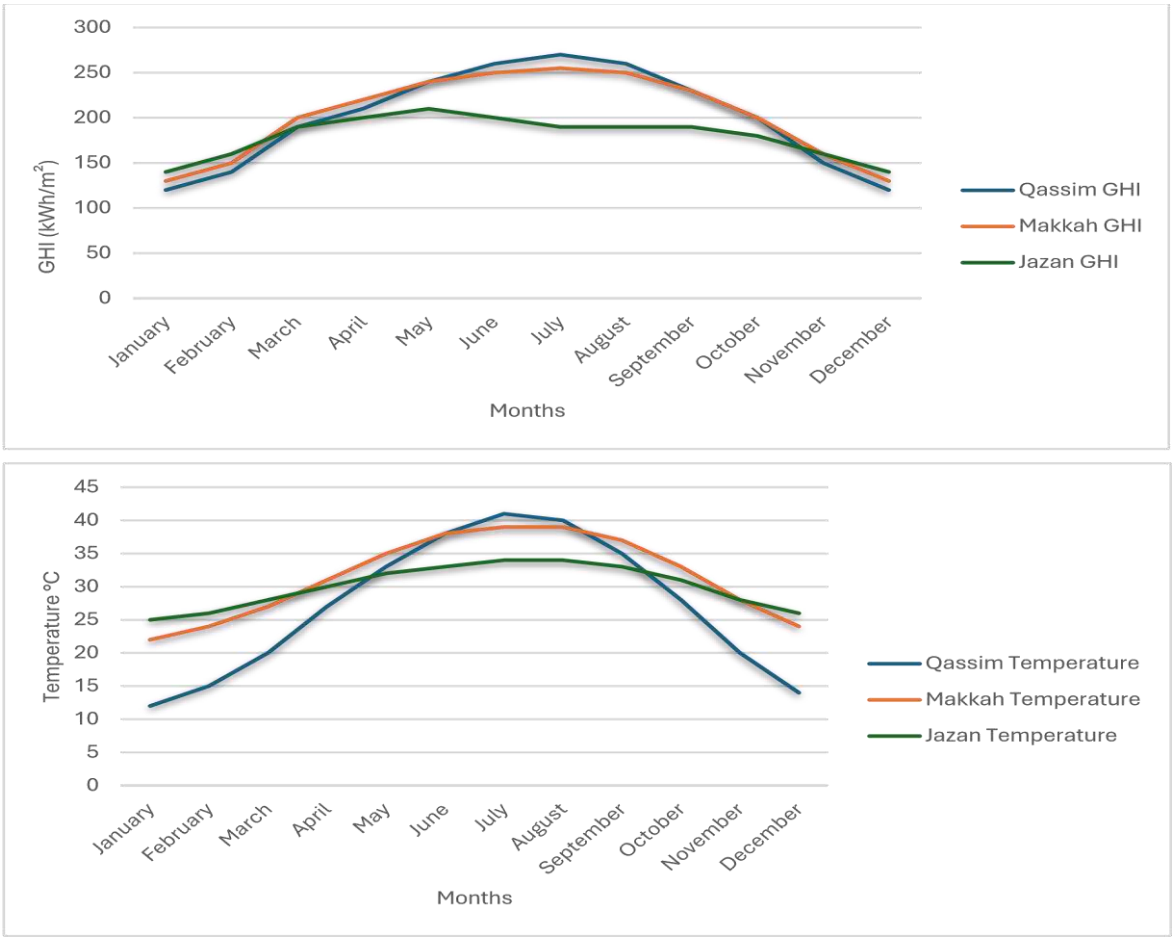


Figure 2. Monthly variation of (a) global horizontal irradiance (GHI) and (b) ambient temperature for the three investigated sites, illustrating climatic diversity across inland desert (Qassim), hot arid (Makkah), and coastal humid (Jazan) regions.

The pronounced differences in solar resource availability and ambient temperature across the investigated sites are illustrated in Fig. 2, highlighting a critical design trade-off in utility-scale PV systems between maximizing solar resource utilization and managing environmental constraints that limit effective energy conversion.

4.2 Annual Energy Yield and Specific Yield

The simulated annual energy production reveals clear variations in both total energy output and specific yield among the three investigated sites. Across the study locations, the annual specific yield ranges from approximately **1,650 to 2,050 kWh/kWp/year**, reflecting the combined

influence of solar resource availability and site-specific climatic conditions. The inland desert site (Qassim) exhibits the highest annual specific yield, primarily due to its consistently high global horizontal irradiance throughout the year. However, during peak summer periods, Qassim does not necessarily achieve the highest monthly specific yield, as elevated ambient temperatures lead to increased thermal losses and reduced PV module conversion efficiency. The Makkah site demonstrates comparable annual energy yield trends, with annual specific yield values generally ranging between **1,780 and 1,980 kWh/kWp/year**. Seasonal reductions in energy production are observed during periods of extreme heat, highlighting the impact of high operating temperatures characteristic of hot arid environments. In contrast, the Jazan site benefits from relatively lower operating temperatures, which contribute to more stable system operation across the year. Nevertheless, its annual specific yield remains comparatively lower, typically within the range of **1,650–1,900 kWh/kWp/year**, mainly due to reduced irradiance availability and increased atmospheric attenuation associated with coastal and humid conditions.

Overall, these results clearly demonstrate that high irradiance alone is not a sufficient predictor of PV performance in high-GHI desert environments. Instead, system performance is governed by the complex interaction between irradiance, temperature, and environmental factors. Instead, annual, and seasonal PV performance in high-GHI regions is governed by the complex interaction between irradiance intensity, ambient temperature, and environmental factors. Temperature-induced efficiency degradation and inverter thermal derating during periods of peak plane-of-array irradiance play a decisive role in shaping the observed energy yield patterns. This seasonal behavior is clearly reflected in the monthly specific yield profiles across the three sites, as illustrated in Fig. 3.

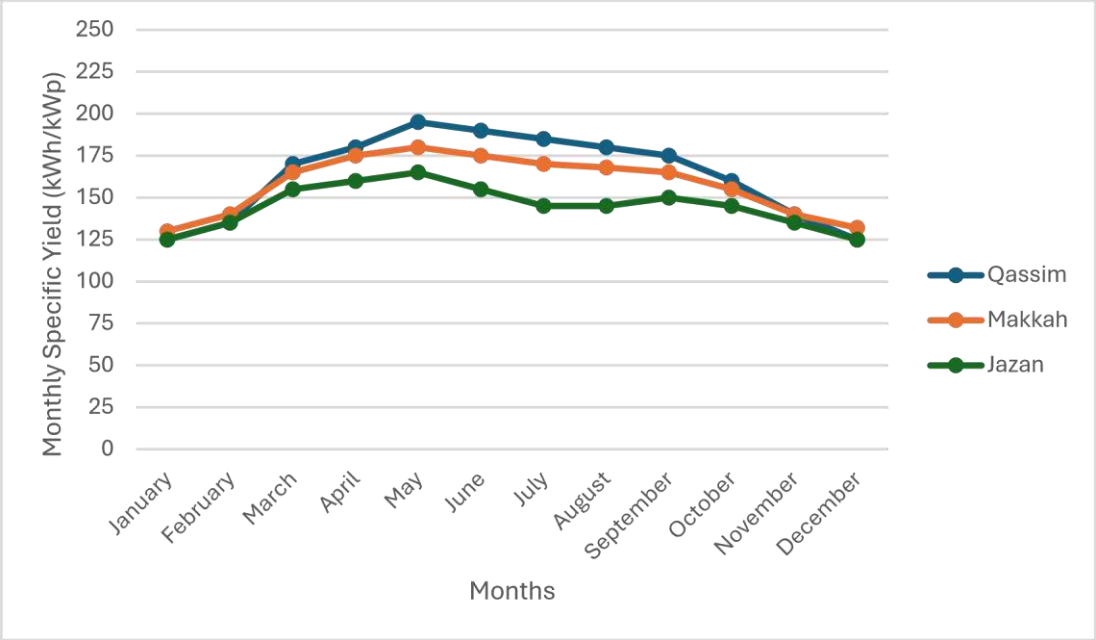


Figure 3. Monthly specific yield profiles of the utility-scale PV systems across the three investigated sites, highlighting seasonal variability and the impact of temperature-related losses during peak summer periods.

The variation in annual energy yield across the investigated sites is illustrated in Fig. 3, highlighting a critical design trade-off where higher solar irradiance does not necessarily translate into higher energy yield due to the increasing impact of temperature and environmental losses.

4.3 Performance Ratio Comparison

The annual performance ratio (PR) analysis further highlights the influence of climatic conditions on utility-scale PV system performance across the investigated sites. Overall, the annual PR values range from approximately **0.76 to 0.84**, with noticeable spatial and seasonal variability. The inland desert site (Qassim) generally exhibits lower annual PR values, typically within the range of **0.76–0.81**, reflecting the pronounced impact of elevated operating temperatures during periods of high solar irradiance. Seasonal analysis indicates a clear reduction in PR during the summer months, coinciding with peak ambient temperatures and intensified thermal losses.

The Makkah site shows a similar PR behavior, with annual values ranging from approximately **0.75 to 0.80**. The combination of high irradiance levels and extreme heat leads to consistent performance degradation during summer periods, despite favorable solar resource availability. In contrast, the coastal site (Jazan) achieves relatively higher PR values, typically in the range of **0.78–0.84**, owing to lower average operating temperatures and reduced thermal stress on system components. However, these advantages are partially offset by increased soiling and atmospheric losses associated with humid coastal conditions.

Collectively, the PR comparison confirms that site-to-site variability results in approximately 3–8% differences in annual PR among the investigated locations. These findings underscore the importance of accounting for climate-specific operating conditions when evaluating and comparing the performance of utility-scale PV plants in high-GHI desert regions. The annual performance ratio comparison across the investigated sites is presented in Fig. 4.

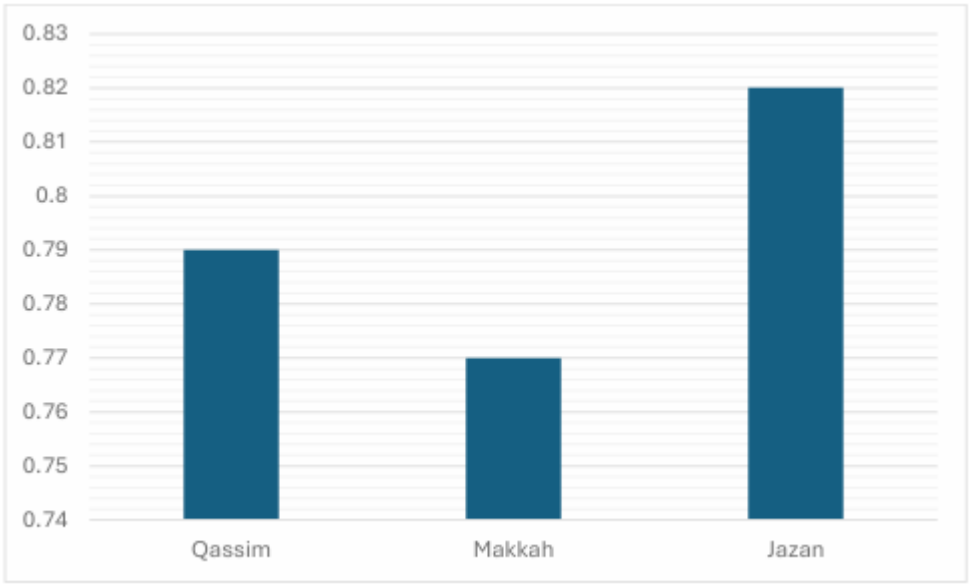


Figure 4. Annual performance ratio (PR) comparison for the investigated utility-scale PV plants, illustrating the influence of climatic conditions on overall system efficiency.

The variation in performance ratio (PR) across the investigated sites is illustrated in Fig. 4, indicating a fundamental trade-off between resource availability and system efficiency, and

clearly demonstrating that higher irradiance does not necessarily correspond to higher PV system performance.

4.4 Loss Breakdown Analysis

The loss breakdown analysis provides deeper insight into the mechanisms governing performance degradation across the investigated sites. Overall system losses are strongly influenced by climatic conditions, with temperature-related losses emerging as the dominant contributor in inland and hot arid regions. For the Qassim site, thermal losses typically account for approximately **7–12%** of the annual energy yield, driven by elevated ambient temperatures and high plane-of-array irradiance that increase PV module operating temperatures and intensify inverter thermal derating. Similar trends are observed for the Makkah site, where thermal losses generally range between **8 and 13%**, reflecting the persistent exposure to extreme heat during extended summer periods.

In contrast, the coastal site (Jazan) experiences comparatively lower thermal losses, typically on the order of **5–10%**, due to lower average operating temperatures and reduced thermal stress on system components. However, this advantage is partially offset by increased soiling-related losses, which are more pronounced in humid coastal environments. Soiling losses at the Jazan site generally range between **3 and 8%**, driven by the combined effects of dust deposition and humidity-enhanced particle adhesion. For the inland and hot arid sites, soiling losses are comparatively lower, typically within the range of **2–6%**, depending on site conditions and cleaning assumptions.

Additional losses associated with inverter inefficiencies, electrical wiring, mismatch, and other system-related factors contribute a smaller but non-negligible share to the overall loss profile. Inverter losses typically range between **1.5 and 3%**, while electrical and ohmic losses account for approximately **1.5–3%** annually. Other losses, including mismatch, light-induced degradation, and auxiliary consumption, collectively contribute on the order of **1–3%**, whereas

clipping losses remain limited, generally below **2.5%**, depending on the selected DC/AC ratio. The dominance of thermal losses in inland and hot arid regions highlights the strong coupling between high irradiance levels and elevated operating temperatures, which jointly amplify performance degradation. These findings emphasize that loss mechanisms in high-GHI desert climates are highly site-dependent and must be carefully accounted for during system design and performance assessment. In particular, strategies aimed at mitigating temperature-related losses and managing soiling effects are critical for improving long-term energy yield and operational reliability of utility-scale PV plants. The relative contribution of different loss mechanisms across the investigated sites is summarized in Fig. 5.

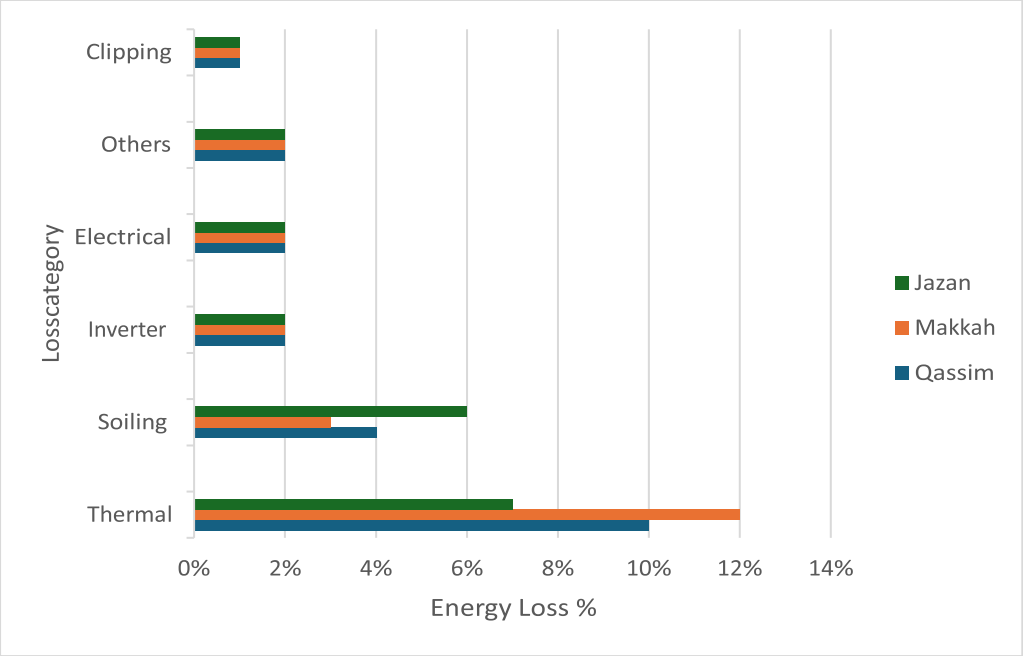


Figure 5. Breakdown of annual energy losses for the investigated utility-scale PV systems, highlighting the relative contributions of thermal, soiling, and system-related losses under different climatic conditions.

The breakdown of annual energy losses across the investigated PV systems is illustrated in Fig. 5, highlighting a critical design trade-off between thermal management and environmental mitigation strategies, which are essential to minimize overall system losses in high-GHI desert environments.

5. Sensitivity Analysis

5.1 Sensitivity of Performance Ratio to Ambient Temperature

To quantify the impact of ambient temperature on the performance of utility-scale PV systems, a sensitivity analysis is conducted by examining the variation of the performance ratio (PR) as a function of average ambient temperature across the three studied sites. Monthly and seasonal temperature profiles are correlated with the corresponding PR values obtained from PVsyst simulations.

The results indicate a clear negative correlation between ambient temperature and PR, particularly during periods of high irradiance. As ambient temperature increases, PV module operating temperature rises, leading to reduced conversion efficiency due to the negative temperature coefficient of power. This effect is most pronounced in the inland desert site (Qassim) and the hot arid site (Makkah), where summer ambient temperatures frequently exceed optimal operating ranges.

A linear regression analysis suggests that PR decreases by approximately 0.35 – 0.45 % per °C increase in ambient temperature, depending on site-specific conditions and system configuration. This trend is consistent with previously reported values in the literature and highlights the critical role of thermal effects in high-GHI desert climates.

The observed temperature sensitivity of performance ratio is consistent with recent findings reported for large-scale PV systems operating in hot climates [30].

These results clearly demonstrate the strong negative impact of ambient temperature on PV system performance, highlighting the dominant role of thermal effects in high-GHI desert environments.

5.2 Sensitivity of Energy Yield to Solar Irradiance (GHI)

The sensitivity of annual specific yield to variations in global horizontal irradiance (GHI) is evaluated by comparing normalized energy output across the three sites. While higher GHI

generally leads to increased energy production, the analysis reveals diminishing returns at very high irradiance levels due to concurrent temperature-related losses and inverter clipping effects. In Qassim, where GHI values are highest, incremental increases in irradiance during peak summer months contribute less to net energy yield than expected under standard conditions. In contrast, the Jazan site exhibits a more linear relationship between GHI and specific yield, reflecting reduced thermal stress but lower overall irradiance availability.

These findings clearly demonstrate that the relationship between GHI and energy yield is inherently non-linear in high-GHI environments, highlighting that higher solar irradiance alone does not necessarily result in proportional increases in energy output due to the combined effects of temperature-induced losses and system constraints.

5.3 Sensitivity to DC/AC Ratio and Inverter Operation

The influence of the DC/AC ratio on system performance is examined by evaluating inverter operation and clipping behavior under different climatic conditions. Higher values of this ratio increase energy harvest during low-irradiance periods but can exacerbate clipping losses during peak irradiance, particularly in high-GHI and high-temperature environments.

The sensitivity analysis shows that, in inland desert conditions, moderate values provide an optimal balance between increased energy yield and acceptable clipping losses. Excessively high values result in marginal gains that are offset by increased inverter clipping and thermal derating. In coastal conditions, the impact of the ratio is less pronounced due to lower peak irradiance and reduced inverter thermal stress.

These results clearly demonstrate that optimizing this ratio should be treated as a climate-dependent design variable rather than a fixed industry standard for utility-scale PV deployment in high-GHI desert environments.

5.4 Comparative Sensitivity Across Climatic Zones

A comparative sensitivity assessment reveals distinct performance drivers across the investigated climatic zones. In Qassim and Makkah, temperature sensitivity dominates overall system performance, whereas in Jazan, environmental factors such as humidity and soiling play a more significant role. This differentiation highlights the need for climate-specific design and operational strategies tailored to site conditions, reinforcing that uniform design approaches may lead to suboptimal PV system performance in diverse environments.

5.5 Implications for Design and Performance Prediction

The sensitivity analysis provides practical insights into how variations in climatic and design parameters influence PV system performance. By quantifying the relative importance of temperature, irradiance, and the DC/AC ratio, the study enables more robust performance prediction and improved risk assessment for utility-scale PV projects in high-GHI desert climates. Integrating sensitivity analysis into early-stage project development can improve design decisions, reduce uncertainty in yield estimates, and enhance the long-term reliability of PV investments in Saudi Arabia and similar environments. These implications reinforce the importance of climate-aware design strategies for optimizing PV system performance in desert environments.

6. Discussion

6.1 Impact of High-GHI and Temperature on PV Performance

The results confirm that high-GHI desert climates offer significant potential for utility-scale PV deployment but also impose substantial thermal challenges. While high irradiance increases energy generation potential, elevated temperatures negatively affect module efficiency and inverter performance, leading to reduced performance ratio (PR) values during peak operating conditions.

This trade-off explains why regions with slightly lower irradiance, but more moderate temperatures may achieve comparable or even higher effective performance under certain conditions. Therefore, accurate modeling of temperature effects is essential for realistic yield prediction in hot climates.

6.2 Climatic Diversity and Performance Variability

Saudi Arabia's climatic diversity plays a critical role in shaping PV performance outcomes. In land desert regions such as Qassim benefit from high solar resource availability but experience significant thermal losses. In contrast, coastal regions such as Jazan are subject to lower thermal stress but higher environmental losses associated with humidity and soiling.

These findings highlight the limitations of single-site assessments for national-scale PV planning and emphasize the importance of multi-site comparative analyses in capturing performance variability.

6.3 Implications for System Design and Operation

The observed performance trends have direct implications for the design and operation of utility-scale PV plants in high-GHI environments. In hot inland regions, design strategies such as optimized DC/AC ratios, inverter selection with improved thermal derating characteristics, and enhanced system ventilation can mitigate temperature-induced losses. In coastal and humid regions, increased cleaning frequency and the use of soiling-resistant module coatings may be more effective in improving long-term performance.

6.4 Comparison with Previous Studies

The results of this study are consistent with previous findings regarding the negative impact of high temperature and soiling on PV performance in arid and semi-arid regions. However, this work extends the existing literature by providing a unified multi-site comparison within a single country using a consistent modeling framework and a hybrid data approach.

By integrating satellite-based climatic data with detailed PVsyst simulations and realistic system specifications, this study offers a comprehensive perspective on utility-scale PV performance in high-GHI desert environments. From an investment perspective, incorporating climate-specific performance adjustments can reduce uncertainty in energy yield forecasts and improve the reliability of techno-economic assessments.

6.5 Limitations and Future Work

Long-term satellite-derived climate datasets and PVsyst simulations using typical utility-scale PV system designs serve as the main foundation for this work. A number of limitations should be noted, even if the hybrid methodology that has been used offers a uniform framework for comparative evaluation across various climatic regions. First, not all of the locations under investigation had access to long-term operational SCADA data from utility-scale PV plants, which limited the direct validation of the simulated energy yields and loss estimations. Second, the models did not specifically account for long-term degradation mechanisms such as module aging, potential-induced degradation (PID), and the temporal development of soiling accumulation and clearance. Additionally, the accuracy of the absolute energy-yield estimations may be impacted by errors related to satellite-derived irradiance and meteorological parameters, especially in areas with inadequate ground-based observations.

Future research should therefore focus on integrating long-term plant-level SCADA measurements with high-quality ground-based meteorological observations to enhance model validation and uncertainty quantification. Further improvements should include physics-based modeling of module degradation, PID, and dynamic soiling behavior, together with machine-learning and hybrid data-driven approaches for improved performance prediction. In addition, climate-adaptive system design and optimization strategies should be investigated to account for evolving environmental conditions and site-specific loss mechanisms. These developments would contribute to more accurate, robust, and reliable assessment of utility-scale PV

performance under the harsh and variable climatic conditions characteristic of desert and coastal environments.

7. Conclusion

This study offers a comparative, climate-driven performance evaluation of utility-scale photovoltaic systems in three different Saudi Arabian climate zones. The findings demonstrate that while high-GHI desert areas provide great potential for solar resources, temperature-induced efficiency losses and site-specific environmental factors considerably limit actual PV performance.

- The results unequivocally show that PV system performance in desert regions cannot be accurately predicted by high solar irradiation alone. Rather, system efficiency and energy yield are mostly determined by the interplay of temperature, irradiance, and ambient factors. While soiling and humidity-related impacts were more noticeable in coastal locations, thermal losses were shown to be the main limiting factor in inland and hot desert regions.
- The performance ratio drops by roughly 0.35–0.45% for every °C rise in ambient temperature, according to sensitivity analysis, underscoring the crucial influence of thermal conditions on PV system efficiency. Furthermore, it was discovered that the relationship between GHI and energy production is intrinsically non-linear at high temperatures, highlighting the significance of climate-aware performance modeling.
- Practically speaking, these results emphasize the significance of site-specific design tactics, such as customized soiling mitigation techniques, better thermal management, and DC/AC ratio optimization. Overall, this work improves system design, lowers uncertainty in the techno-economic evaluation of utility-scale PV projects in high-GHI desert conditions, and improves yield prediction.

Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Author contributions

Hadi Ali Madkhali: Conceptualization, Formal analysis, Investigation, Visualization, Supervision, Validation, Funding acquisition, Review & editing of the original draft.

Funding

The authors extend their appreciation to the Deanship of Scientific Research of Jazan University for funding this research work through the project number (project number will be provided at the proof level later)

Declarations

Competing interests

The authors declare no competing interests.

Ethics Statement

The authors declare that this study does not involve any human participants or animals. Therefore, ethical approval and informed consent are not required for this research. The authors confirm that the research is conducted in accordance with relevant academic and ethical guidelines.

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