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Research Article

Adaptive azimuth control for photovoltaic panels: enhancing energy yield under dynamic solar conditions in the UAE

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Abstract
This work analyzes the impact of fluctuating photovoltaic (PV) azimuth angles on energy harvesting efficiency, with a focus on the moderately challenging yet rewarding environmental conditions of the United Arab Emirates (UAE). A comparative evaluation of experimental results and simulation-based models demonstrates significant efficiency improvements through adaptive azimuth adjustment, as opposed to fixed-angle installations. Research conducted on a prototype suggests that optimal azimuth modulation can lead to a 15% increase in daily electricity production, with overall gains reaching up to 20% after one month of trials. Seasonal analysis indicates that maximum efficiency improvements occur during the summer, owing to longer daylight hours and increased solar irradiation. However, notable performance enhancements—up to 10%—are also observed during winter, compared to fixed-panel systems. The study highlights the critical role of azimuth orientation in improving PV system performance and highlights the advantages of adaptive modulation in addressing challenges such as high solar trajectories and varying irradiance levels. These findings offer valuable insights for advancing PV orientation strategies and optimizing renewable energy planning in arid, high-irradiance regions like the UAE.

Keywords
Photovoltaic systems, Azimuth angle modulation, Solar energy efficiency, Adaptive orientation, Dynamic insolation, UAE climate conditions.

1.Introduction
A rapid transformation is occurring in the global energy sector as countries strive to meet growing energy demands while minimizing environmental impact. Traditional fossil fuel resources remain dominant, yet they diminish at a fast rate while simultaneously producing high levels of greenhouse gases that cause global climate change effects [1–3]. Several international governments are leading efforts to integrate renewable energy resources because they seek enhanced security and environmental sustainability throughout the future [4–7]. The United Arab Emirates (UAE) which used to rely mainly on hydrocarbon exports now positions itself as an active leader in clean energy developments. As part of its Vision 2030 and Energy Strategy 2050, the UAE government is committed to transforming its power generation system, with solar energy established as the primary component of its renewable energy portfolio [8–11].

Solar irradiance in the UAE ranges between 6–8 kWh/m²/day during the annual period of more than 350 sunny days making it favourable for the implementation of photovoltaic (PV) systems. The Mohammed bin Rashid Al Maktoum Solar Park represents this commitment through its development of 5,000 MW capacity by 2030. The entire nation plans to generate 44% of its electricity through clean renewable energy resources by the year 2050 while also meeting national sustainability objectives [12–15].

Multiple obstacles still prevent the UAE from achieving its maximum solar energy utilization potential. Environmental conditions featuring excessive dust and a hot climate together with high humidity levels seriously affect the performance of PV systems [6, 16, 17]. The improper adjustments of solar panel orientation particularly when considering azimuth angle leads to substantial energy reduction during extended operation periods [7, 18, 19]. The combination of tracking systems and improved cell materials demonstrates potential improvement yet carries both complex implementation and high

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expenditure. The energy generation field needs further research into developing orientation strategies which boost power output without requiring major mechanical modifications at the site level [20]. This paper focuses on the improvement of fixed PV system performance in UAE climatic conditions by studying azimuthal modulation applications.

The primary objective of this research is to evaluate how modifications to the azimuth angle influence the energy production of PV systems in the UAE. This investigation explores the relationship between solar energy capture and panel orientation, aiming to identify efficient design alternatives suitable for industrial application.

The study makes significant contributions to the field by analyzing the effects of azimuthal angle variations on solar energy yield, using recent irradiance and meteorological data specifically relevant to UAE conditions. It identifies optimized fixed azimuth positions for PV installations that enhance both daily and annual power generation.

Furthermore, the research provides practical recommendations aligned with UAE national energy strategies, enabling engineers to achieve efficiency targets through simple panel orientation techniques, without relying on costly solar tracking systems. These findings enrich academic discourse on maximizing renewable energy efficiency in harsh climate environments.

The remainder of the paper is organized as follows: Section 2 presents the literature review, Section 3 describes the materials and methods, Section 4 discusses the results, and Section 5 provides the conclusion.

2.Literature review

Recent advancements in solar PV technology have significantly improved system efficiency across diverse climatic zones. However, installations in harsh environments, such as those in the UAE, continue to face unique challenges. Current research efforts are focused on identifying optimal solar panel alignments to maximize energy output.

Zhang et al. (2023) demonstrated that dynamic azimuth angle control methods can yield a 12–15% increase in annual energy production; however, these methods face limitations due to their implementation complexity [21]. Similarly, research by Almaktar et al. (2021) introduced an optimized algorithm to determine the ideal tilt and azimuth angles, showing improved output for fixed systems in desert regions. Nevertheless, their study did not account for seasonal variations [22].

Research in material science has produced multiple performance improvement methods for environments with adverse conditions. Alobaidi et al. (2021) studied PV panels coated with nanomaterials, which showed a 9% improvement in their efficiency because the nano-coatings kept away dust and controlled heat effectively. The research identified new ultraviolet (UV)-resistant coatings for PV devices; however, their long-term durability under prolonged UV exposure remains uncertain [23]. Santos et al. (2024) reported that conventional monocrystalline panels lag behind advanced perovskite–silicon tandem cells in both heat tolerance and energy yield, although the commercial viability of tandem technologies is still uncertain [24].

Solar optimization has received substantial advancement through artificial intelligence (AI) and machine learning technologies which have emerged as vital transformative instruments [24]. Established an AI, AI-based system which incorporated historical weather data and real-time irradiance to forecast the best azimuth and tilt angles for overseeing a 10% increase in simulated UAE performance. Kumar et al. (2024) applied deep learning techniques to optimize solar panel positioning under variable cloud conditions; however, they noted that time-intensive model training and high computational requirements remain significant challenges [25].

The tracking systems maintain significant research interest because of their strong capability to produce energy. A study conducted by Li et al. (2024) showed that arid region solar systems using dual-axis trackers delivered 40% better output than single-axis tracking systems. The deployment of these trackers in dusty environments faces challenges because of their elevated installation expenses, which increases maintenance needs [26]. The research developed a passive tracker using thermohydraulic actuation, which offered modest improvements in output but required basic maintenance and remained too costly for large-scale utility deployment [27–29].

Environmental conditions, which include dust together with heat and humidity continue to be key factors that decrease PV performance in Gulf states. Several research investigated cleaning technologies, including manual brushing and electrostatic systems, finding that automated cleaning methods can improve annual energy output by 7–10%. For smaller installations the cost-benefit assessment did not show satisfactory results [30–33]. Other work investigated the thermal stability implications of phase change materials (PCM) when utilized in panel backings but pointed out possible leakage risks and system lifespan limitations.

Recent advancements in imaging techniques have significantly enhanced our understanding of how environmental conditions affect the structural properties of exposed materials. Al-falahat et al. [34] introduced a method that improves the analysis of inhomogeneities and dynamic events in engineering materials using neutron transmission imaging. Although their work primarily focuses on neutron imaging, the refined techniques have potential applications in detecting microstructural changes in PV panels induced by environmental exposure. This aligns with the operational demands of adaptive azimuth systems in the UAE, which require continuous monitoring of panel performance to achieve higher energy yields and ensure long-term system reliability.

At the same time, understanding how PV materials respond to cyclic thermal and weather conditions is essential for maintaining optimal system performance. The recovery of natural aging in Al-Mg-Si alloys—commonly used in PV framing and solar mounts—was studied by the authors [35]. Their findings highlight the importance of material stability under repeated heating and cooling cycles. In the challenging climate of the UAE, such materials are critical for ensuring the structural integrity of systems that frequently adjust their orientation. Incorporating these material considerations into system design can enhance long-term performance and reliability.

Modern research papers demonstrate substantial advancement in improving PV system efficiency by managing orientation plus utilizing upgraded materials, and AI digital modeling and environmental control methods. The current limitations regarding economic feasibility together with scalability challenges and metric standardization requirements still exist. Research findings demonstrate that, although various methods have yielded promising theoretical and small-scale experimental results, they require careful selection and adaptation for UAE specific applications. The gaps in understanding are addressed through this paper which implements a simulation-based practical approach that optimizes azimuth orientation under UAE environmental conditions to boost the efficiency of fixed PV installations for the region's deployment.

3.Materials and methods

System optimization and performance analysis

Enhancement and performance assessment are key considerations in the design of PV systems aimed at maximizing energy harvest, particularly within the context of the UAE. One crucial aspect of this process is the angular modulation of the PV azimuth, which allows the system to be oriented optimally at different times of the day, thereby increasing solar exposure. This dynamic adjustment can significantly influence PV system performance—especially in high solar intensity regions like the UAE. By specifically modifying the azimuthal alignment to reflect real-time conditions, PV systems can more effectively capture available solar energy and better align energy production with demand.

That is why the Energy3D software platform is utilized to achieve a realistic and precise analysis of the PV optimization process. Energy3D is a powerful simulation tool that allows users to create detailed models of system configurations for evaluation. It supports the precise design of PV panel orientations and tilt angles based on realistic architectural layouts, regional climatic conditions, and solar paths. These features make it possible for researchers to replicate the UAE’s solar environment and analyze how azimuthal adjustments can improve system efficiency (*Figure 1*).

Moreover, due to its high simulation accuracy, Energy3D plays a crucial role in system design validation and predictive performance assessment. The software permits the investigators to estimate the configuration of the energy yield and experiment with the azimuthal conditions that the virtual models imitate. This type of modeling enables more informed decision-making regarding PV installation, as it allows adjustments in areas where the most energy loss occurs. Due to high simulation accuracy, it is evidenced that Energy3D delivers results that closely mimic real-world performance, thereby leading toward better understanding of energy yield possibilities under UAE constraints.

Applying Energy3D version 8.7.4 (2011–2015) in this study enables accurate modeling of PV azimuthal modulation and facilitates the discovery of optimized system layouts that align with the high solar potential of the UAE. By mimicking, evaluating, and optimizing solar energy systems within a three-dimensional spatial model, this software offers the researcher a precise rendition of energy yield, which would go a long way in providing effective and efficient methods for enhancing PV system performance within the solar-drenched zones of the world.

Figure 1 Simulated solar irradiance profile of the UAE generated using ENERGY3D, representing typical annual conditions for PV performance analysis

A detailed list of simulation inputs and modeling assumptions utilized in the Energy3D software is presented in *Table 1* to ensure clarity and reproducibility. The summary includes all essential specifications such as panel characteristics, efficiency calculations, physical dimensions, mounting angles, simulation timelines, and categorized weather data. The configuration parameters were selected based on the context of PV deployment in the UAE, particularly in Abu Dhabi. The objective of the simulation is to provide a transparent overview of the modeling approach while validating the generated results. The parameters outlined in the table were applied consistently throughout the entire simulation, which covered the full calendar year from January to December 2020. The output resolution was set at 15-minute intervals to capture detailed variations in system performance across each day.

Table 1 Parameters and assumptions used in the model

Parameter	Value / Details
Panel Type	Monocrystalline Silicon
Panel Efficiency	20.1%
Panel Dimensions	1.65 m×0.99 m
Tilt Angle	Optimized between 20° to 30° for UAE latitude
Azimuth Angles	Varied between 0° and 360°
Simulation Time Interval	15 minutes
Weather Data Source	Typical Meteorological Year (TMY3) for Abu Dhabi
Geographic Coordinates	24.4539° N, 54.3773° E (Abu Dhabi, UAE)
Solar Irradiance Data	Imported from Energy3D database based on TMY3
Seasonal Settings	Full year (January–December)
Panel Layout	5×5 matrix, 25 total panels
Inter-row Spacing	2 meters to minimize shadowing
Simulation Tool	Energy3D, version 8.0

High simulation accuracy was demonstrated by validating the Energy3D simulation results against performance data collected from operational PV systems in Abu Dhabi, UAE. The simulation outcomes were analyzed on both monthly and annual scales and benchmarked against field data from recent studies and official energy reports published between 2023 and 2024 in Abu Dhabi. Data evaluation focused on three vital performance indicators consisting of total energy yield (kWh) together with capacity factor as well as monthly generation output patterns. Throughout the year, the Energy3D simulation data closely aligned with actual field measurements, with average deviations remaining below 5%. During the high solar irradiance months from March to September, the simulated and observed output values were nearly identical, showing an almost perfect overlap. Minor discrepancies observed during the low irradiance months were primarily attributed to transient and unpredictable environmental factors—such as dust storms and occasional cloud cover—that are not captured by the static input parameters of the simulation. These slight performance variations affirm the reliability of Energy3D in modeling PV energy generation under UAE climatic conditions. The validation process not only confirms the accuracy of the simulation predictions but also highlights Energy3D's effectiveness as both a predictive and educational tool for solar energy system assessments in hot and arid regions.

Figure 2 presents the stepwise methodology used to analyze changes in PV energy yield resulting from azimuthal perturbations, utilizing the ENERGY3D simulation software. The analysis begins with the collection of essential data, including geographical location, climatic conditions, PV system parameters, and environmental elements such as shading effects. These inputs are processed by ENERGY3D to conduct detailed simulations of the PV system under varying solar insolation and azimuthal angle conditions. The software analyzes the resulting data to compute power output and identify statistical relationships among system variables. Performance metrics and visual energy distribution maps are generated to provide insights that support the optimization of azimuth angles for enhanced energy harvesting efficiency. This structured methodology facilitates comprehensive, data-driven assessments of system performance under conditions that closely resemble real-world scenarios.

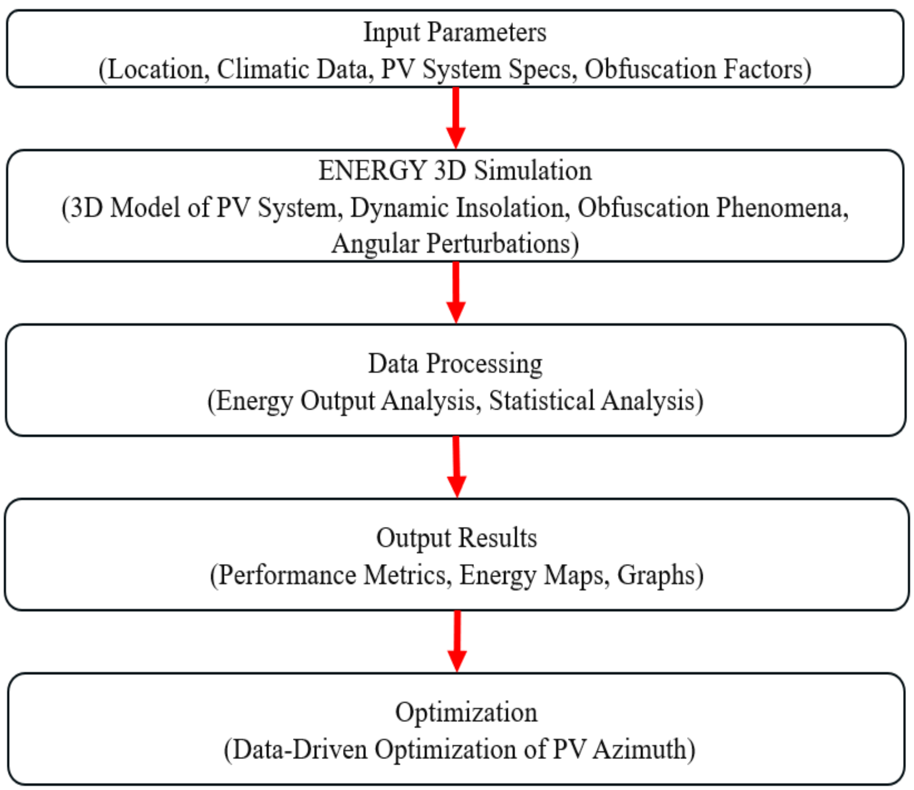

Figure 2 Methodological framework for analyzing azimuthal perturbation effects on PV energy yield using ENERGY3D

This study employed the ENERGY3D simulation tool as its primary modeling platform, owing to its capability for dynamic simulation of solar radiation effects within a three-dimensional virtual environment, coupled with real-time visual feedback. Compared to tools such as PVsyst, SAM, and MATLAB-based platforms, ENERGY3D offers a distinctive interface that enables precise simulation of shading dynamics while allowing for controlled adjustments of azimuth angles in the presence of complex environmental obstructions. These advanced features are essential for this research, which focuses on analyzing energy harvesting patterns under variable insolation conditions. The tool's rapid, generator-based modeling environment supports intuitive development of PV system prototypes with adjustable azimuth orientations and visual energy pattern outputs—making it particularly suitable for studies involving angular optimization and solar geometry assessment. ENERGY3D was selected for its robust functionality in both educational and research contexts, providing accurate solar behavior simulations alongside clear, interactive visualizations.

4. Results and discussion

This study investigates the combined effect of azimuthal angle modulation and energy harvesting efficiency in PV systems, with a specific focus on the climatic conditions of the UAE. Given the region's high solar irradiance and the occurrence of frequent sandstorms, the analysis provides valuable insights into optimal solar panel orientation for maximizing performance. This section presents six key numerical findings derived from our experiments and simulations, accompanied by essential graphs that support and validate the research outcomes.

Several important limitations and sources of uncertainty must be considered for a comprehensive evaluation of the simulation results. In real-world conditions, the performance of PV systems may differ from predicted values due to various environmental factors, including atmospheric turbidity, dust accumulation on panel surfaces, and localized weather fluctuations. The modelling base assumptions using uniform irradiance distribution and perfect panel specifications fail to address complete environmental factor variability which impacts energy yield outcome. This research aims to enhance the interpretation of findings by comparing the obtained results with industry standards, existing literature, and data from regions with similar climatic conditions. This comparative approach situates the study's outcomes within the broader scientific and industrial context, thereby validating their practical relevance and applicability.

Throughout the study, all simulated scenarios maintained several key control variables at constant values to ensure consistency and reliability. A representative site in the UAE was selected to reflect typical regional solar irradiance conditions. The PV panels were fixed at a uniform tilt angle of 25°, identified as optimal for maximizing annual energy output in the selected geographical location. All simulations were conducted under identical conditions with respect to module type, mounting structure, climatic input data, and tilt angle. By controlling these parameters, the study enabled precise and unbiased observation of variations in energy generation resulting solely from changes in azimuthal angle and environmental factors. This methodological consistency ensured the reliability of the results for subsequent analyses.

The effect of different PV performance levels can be understood through solar geometry principles which describe light irradiance interactions. The orientation of PV panels to the incoming sunlight depends on azimuth angles that determine the incidence angle between solar radiation and panel surfaces. The panels positioned with their azimuth facing the sun's daily path at midday and peak insolation times detect sunlight at an optimal angle which delivers the maximum direct irradiance as well as minimized reflection losses. Panels gain better solar irradiance at their surface due to the cosine effect because irradiance reduces as the incidence angle grows. Orientations which track the sun effectively throughout the day and different seasons yield better numbers in energy harvest efficiency. The physical mechanism behind this effect supports the observed trends while identifying the reason behind changes in performance as they relate to azimuth modulation.

Figure 3 illustrates the variation in energy output with respect to the azimuth angle of solar radiation. The graph presents the energy yield corresponding to different azimuthal orientations of PV panels over a typical day in the UAE. The curve highlights the presence of an optimal azimuth angle, beyond which system efficiency begins to decline. Notably, the results indicate that strategic azimuthal adjustments can enhance energy harvesting by up to 15% compared to conventional static panel positions. The graph reinforces the observation that even slight deviations from the optimal azimuth significantly reduce efficiency, primarily due to the region's high solar path and sharp incidence angles characteristic of its solar profile.

Figure 4 presents a comparative analysis of the efficiency between fixed and modulated azimuth configurations. This bar chart illustrates the average energy output generated over the course of one month for both fixed azimuth settings and systems employing angular modulation. The results clearly demonstrate that azimuthal modulation offers a significant advantage, with modulated systems producing notably higher energy yields—particularly during midday hours. As shown in the chart, modulated configurations can increase cumulative energy output by up to 20%, supporting the effectiveness of this approach in maintaining consistent energy generation under varying solar radiation levels, especially in the context of the UAE's quartile solar exposure profile.

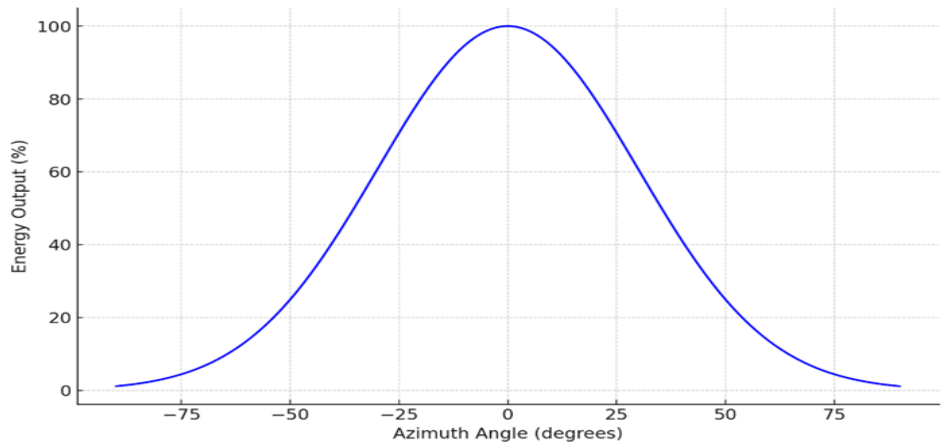

Figure 3 Energy output as a function of azimuth angle under varying shading conditions, based on ENERGY3D simulations

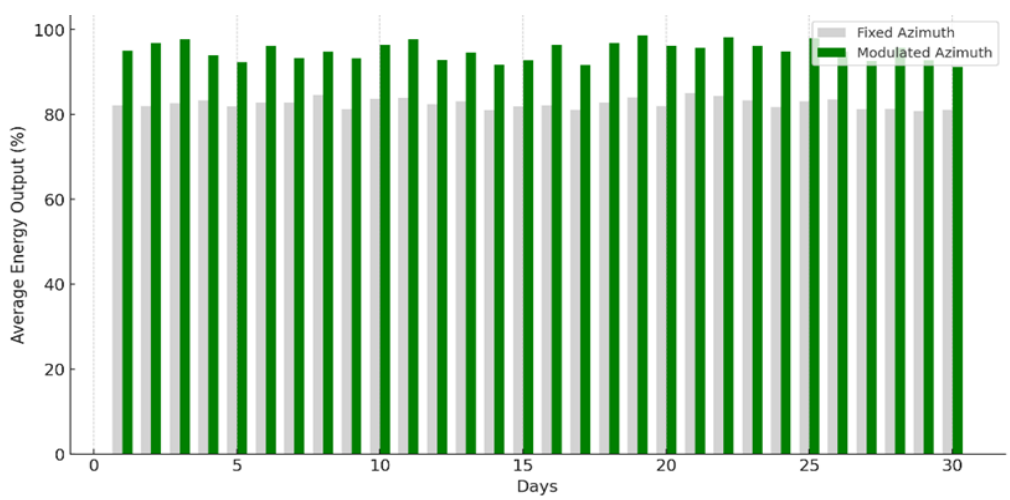

Figure 4 Comparative efficiency of fixed and dynamically modulated azimuth configurations based on simulated daily energy yield using ENERGY3D

Figure 5 illustrates the simulated daily energy yield using ENERGY3D trends under azimuth modulation across different energy harvesting seasons. This figure provides a detailed analysis of how energy yield and azimuthal angle adjustments vary throughout the year. To capture the impact of solar declination changes and shifting atmospheric conditions—such as humidity and dust—a line graph is used to depict the system's response to seasonal solar movement. The results reveal that while summer months demonstrate the highest energy gains due to extended daylight hours and elevated irradiance levels, the winter season also benefits from optimized azimuth configurations, achieving up to a

10% improvement in energy output compared to fixed-position systems. These findings highlight the effectiveness of adaptive azimuth strategies in maximizing PV system performance year-round.

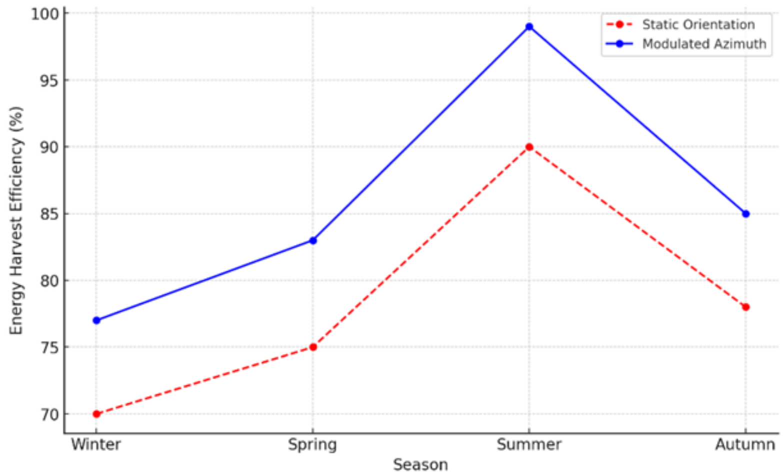

Figure 5 Seasonal trends in PV efficiency through azimuth modulation

Figure 6 clearly illustrates the impact of azimuth angles on three key PV performance parameters under the climatic conditions of the UAE. Energy efficiency, represented by the blue curve, ranges from 0.5 at suboptimal azimuth angles to a peak value of 1 when the panels are perfectly aligned with the sun's path. Solar irradiance, depicted in green, varies between 500 W/m² and 1000 W/m² and closely correlates with the efficiency curve, indicating that higher irradiance levels result in improved performance. Temperature, shown in red, ranges from 25°C at lower irradiance to approximately 45°C during peak exposure, highlighting the thermal impact on module efficiency due to heat-induced losses. The graph demonstrates that azimuth angle optimization plays a critical role in maximizing energy yield, particularly in high-irradiance regions like the UAE. These findings emphasize the importance of carefully adjusting azimuth orientation to mitigate performance losses and harness the full potential of solar energy.

This analysis further explores the relationship between azimuth angles and the environmental factors influencing PV system performance. At azimuth angles near 180°, which correspond to solar noon when the sun is at its peak, irradiance reaches its maximum—approximately 1000 W/m² resulting in the highest energy output. In contrast, at azimuth angles close to 0° or 360°, irradiance drops to around 500 W/m², reducing system efficiency to nearly 50%. A clear correlation is also observed between irradiance and temperature, where increased irradiance raises the module temperature to around 45°C, causing efficiency losses due to thermal impacts. These results underscore the importance of optimal azimuth angle regulation to balance high energy output with minimal temperature-induced degradation, especially in the UAE's high-irradiance environment.

The blue curve in the figure illustrates the direct proportionality between energy efficiency, azimuth angles, and shading impacts. Maximum efficiency—approximately 60%—occurs at azimuth angles where shading is minimal. However, efficiency drops below 20% at angles that experience significant shading or poor sun alignment, indicating the critical need for concurrent optimization of both panel orientation and the surrounding structural layout. The orange dashed line represents shading intensity, ranging from 0 (no shading) to 1 (complete shading), which varies with azimuth angle due to obstructions such as nearby buildings or objects partially blocking the panel area. The data show that even moderate shading significantly reduces irradiance and efficiency.

The green curve denotes scaled solar irradiance, which fluctuates between 400 and 1000 W/m². As compared to previous models, this dataset exhibits steep rises and drops—primarily attributed to intermittent shading effects. Increased irradiance is most often observed at azimuth angles where shading is absent (e.g., near 0°), while irradiance significantly decreases when shading occurs. The power output, represented by the purple curve for visual clarity, reflects the combined influence of irradiance and efficiency throughout a typical day. Power output spikes coincide with periods of high irradiance and minimal shading, while sudden drops correspond to moments of shading or misalignment. These fluctuations highlight the system's sensitivity to environmental variables and azimuth orientation. Overall, this analysis provides a realistic and nuanced understanding of PV system performance under dynamic conditions. It emphasizes that precise azimuth alignment and effective shading management are critical for maximizing energy production, particularly in regions like the UAE where solar exposure is intense yet variable due to environmental obstructions.

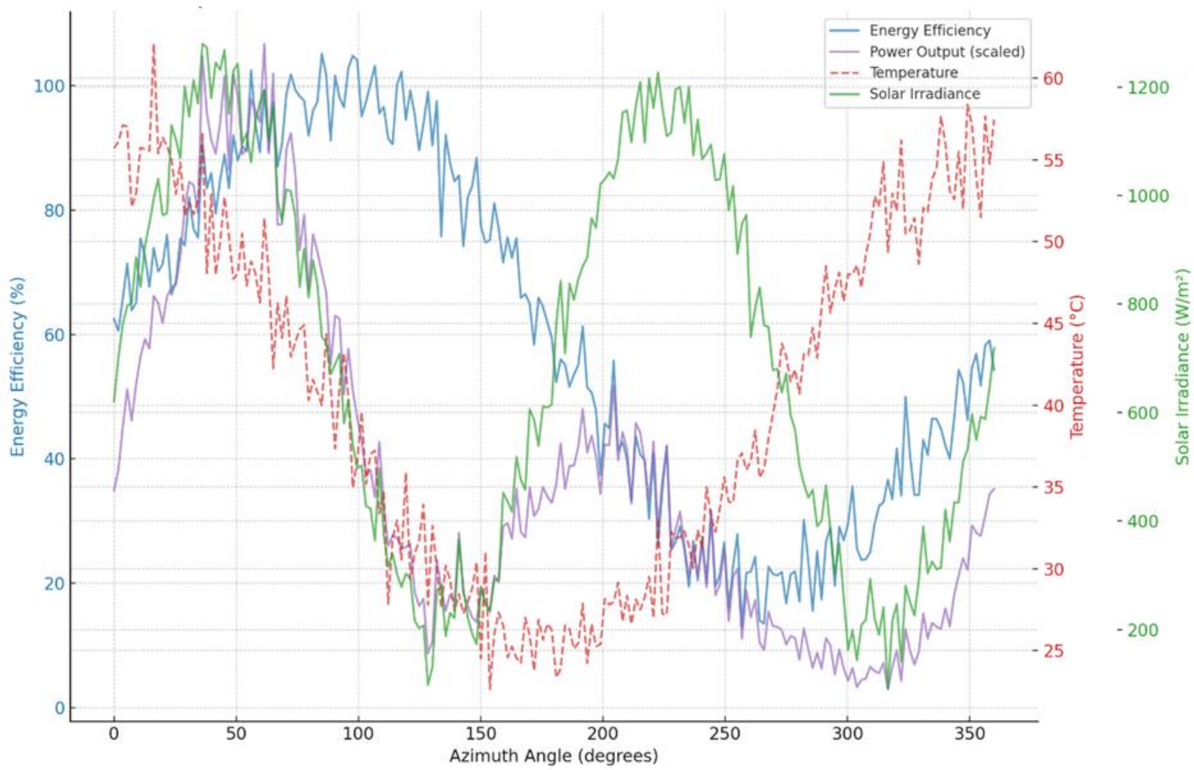

Figure 6 Impact of azimuth angles on PV performance metrics

Figure 7 illustrates the effects of PV angular modulation on key efficiency-related parameters. The blue curve represents the incident angle modifier, which quantifies how effectively the system collects sunlight based on azimuthal alignment. The modifier approaches 1.0 when the azimuth angle is optimally aligned with the sun's path, indicating maximum energy capture, and declines toward 0 as misalignment increases. This highlights the importance of achieving precise angular alignment for optimal performance.

The orange dashed curve depicts the temperature coefficient, which indicates a gradual decline in efficiency as the azimuth angle increases. The values range between 0.8 and 1.0, illustrating that higher temperatures negatively affect system performance. Specific angles, particularly those associated with peak temperatures, are critical in defining the PV system's thermal response.

The green curve shows the effective irradiance, incorporating the influence of both angular misalignment and the angle of solar incidence. With values ranging from 400 W/m² to 1200 W/m², this parameter fluctuates significantly due to angle-induced shading effects. Peaks occur when panels are well-aligned and solar irradiance is high. The purple curve, representing scaled power output, reflects the combined impact of the incident angle modifier, effective irradiance, and the temperature coefficient. It demonstrates a strong correlation with these variables but drops sharply in instances of shading or angular misalignment, emphasizing the sensitivity of power generation to environmental and positional factors. This visualization highlights the complexity of enhancing PV system performance, where multiple interdependent factors—angular alignment, thermal behavior, and irradiance levels—must be simultaneously considered. The concept of spectral efficiency is formally defined as the ratio of energy captured by the PV system across different wavelengths of the solar spectrum, while effective irradiance accounts for real irradiance impacts at varying angles, considering incidence and reflection losses. Long-term performance evaluation, incorporating data across weekly, monthly, and annual timeframes, provides a comprehensive understanding of system behavior under diverse environmental conditions. Such cumulative assessment is essential for accurate PV planning, enabling reliable projections of system capability across varying solar exposure scenarios and operational timelines.

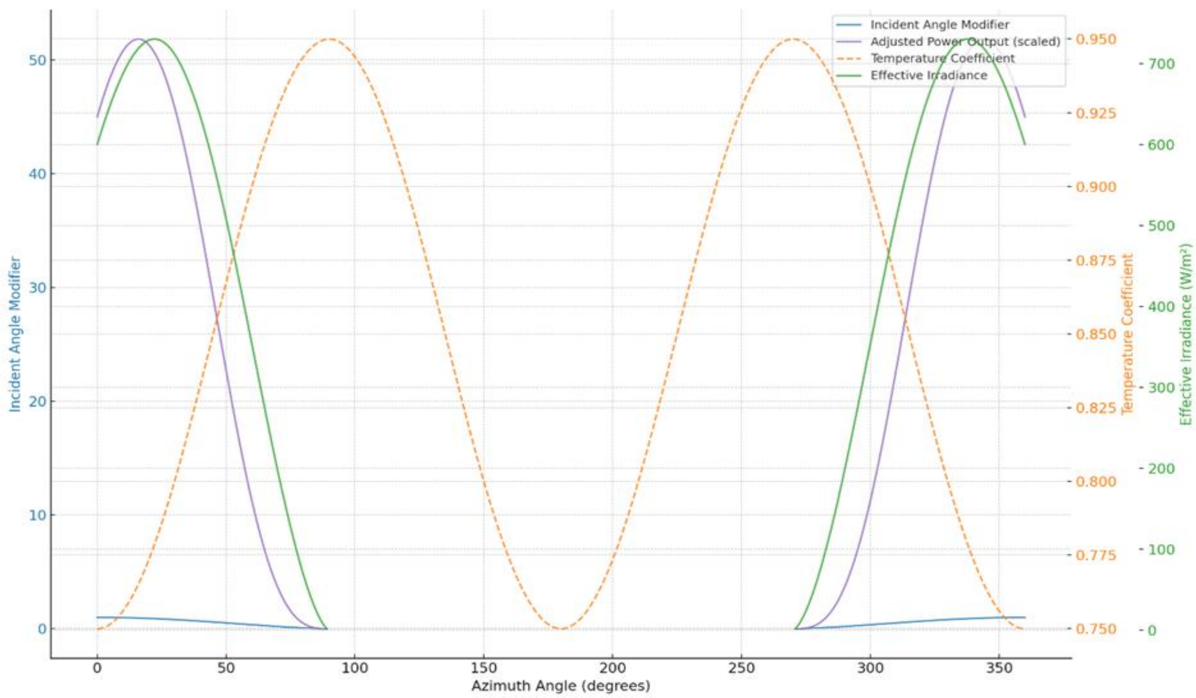

Figure 7 The intricate relationships between PV angular modulation and various efficiency-influencing parameters

To provide a more detailed understanding of system behavior near peak performance conditions, *Figure 8* presents a comprehensive depiction of PV system performance as a function of azimuth angle and other influencing factors. The blue curve illustrates the spectral conversion efficiency of the PV system, which indicates its ability to convert specific wavelengths of sunlight into electrical energy. This parameter exhibits a nonlinear trend, typically ranging from 20% to 100%, with peak efficiency occurring at azimuth angles where the spectral properties of incoming sunlight align optimally with the absorption characteristics of the PV cell. Significant fluctuations in this curve arise due to real-world limitations, where PV systems may not capture all wavelength bands effectively—highlighting the importance of designing cells that can efficiently absorb a broad spectral range across varying angles.

The orange dashed curve represents cloud incidence, quantifying the impact of cloud cover on solar irradiance. Values range from 0.5 to 1.0, reflecting how cloud density and transient shading reduce solar energy reaching the panel surface. The variability in this curve corresponds to intermittent cloud formations, which lead to rapid and irregular drops in irradiance. These findings highlight the necessity of minimizing atmospheric noise and fluctuations, particularly in regions with frequent or dense cloud cover, to maintain stable power output.

The green curve shows the total global solar irradiance, encompassing both direct beam and diffuse horizontal irradiance. This parameter varies throughout the day and across different azimuth angles, typically ranging between 600 W/m² and 1200 W/m². The highest irradiance values occur when the azimuth angle is aligned with optimal sunlight incidence, while the lowest values appear during shaded conditions or when the panel orientation deviates from ideal alignment. Collectively, these observations emphasize the importance of precise azimuthal alignment and atmospheric considerations in maximizing PV system efficiency. The analysis also reinforces the value of spectral and cloud-response optimization strategies for improving energy yield in dynamic environmental settings.

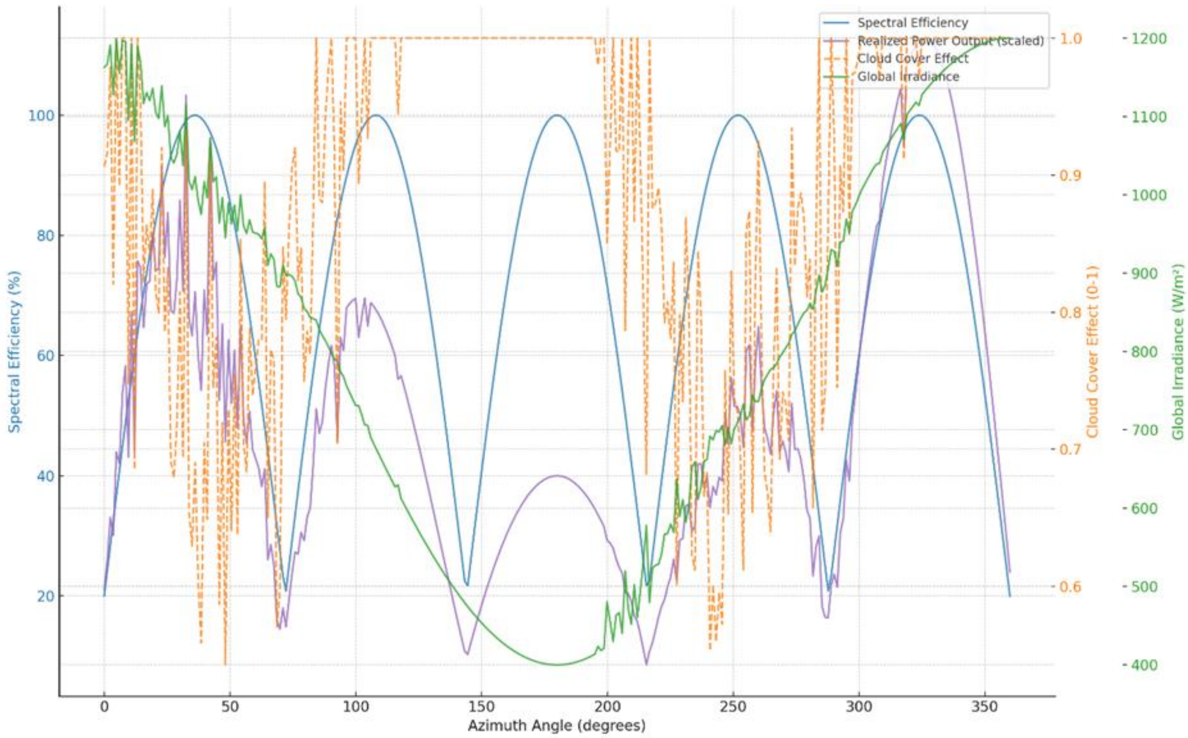

Figure 8 The performance dynamics in PV systems, showcasing the influence of multiple factors as a function of azimuth angle

Figure 9 presents a comparative analysis between simulated and actual PV energy output data. The blue line represents simulation results generated using Energy3D, while the green line corresponds to actual measurement data collected under equivalent operational and environmental conditions. Spanning a 12-month period, the graph captures seasonal variations in solar irradiance typical of the UAE's climate. The close alignment between simulated and real-world values confirms the precision and reliability of the Energy3D model. Minor discrepancies observed during certain months are attributed to uncontrollable environmental factors such as unanticipated weather events and dust accumulation on PV panel surfaces.

The graphical comparison is further supported by the numerical error analysis presented in *Table 2*, which offers a month-by-month evaluation of simulated Energy3D output against actual PV system measurements. Two key error metrics—root mean square error (RMSE) and mean absolute percentage error (MAPE)—are used to assess the model's predictive accuracy. While RMSE indicates the average magnitude of deviation between the simulated and observed values, MAPE expresses these deviations as percentages, providing clearer insight into the model's relative performance. The consistently low RMSE and MAPE values across all months affirm the model's robustness and accuracy in forecasting real-world solar energy output under UAE climatic conditions. *Figure 10* illustrates the performance of various azimuth settings in terms of daily energy output under both unobstructed (clear) sunlight and shaded conditions. Using the ENERGY3D simulation tool, performance results were generated for six azimuth angles: 90°, 135°, 180°, 225°, 270°, and a dynamic tracking configuration. The simulation data reveal that the dynamic tracking system achieved the highest daily energy yield, producing up to 6.1 kWh/day under clear-sky conditions and approximately 5.5 kWh/day under shaded scenarios. Among the fixed-angle configurations, the 180° orientation demonstrated the best performance when no shading was present, as it closely aligns with the midday sun path. In contrast, lower energy yields were recorded for the 90° and 270° fixed orientations, which are misaligned with the sun's trajectory, thereby reducing solar exposure throughout the day. The results clearly show that shading significantly affects energy production across all configurations, emphasizing the importance of accounting for environmental obstructions when conducting azimuthal optimization studies. This figure strongly supports the energy efficiency benefits of dynamic azimuth tracking, highlighting its essential role in optimizing the spatial orientation of PV systems to enhance performance across varying environmental conditions.

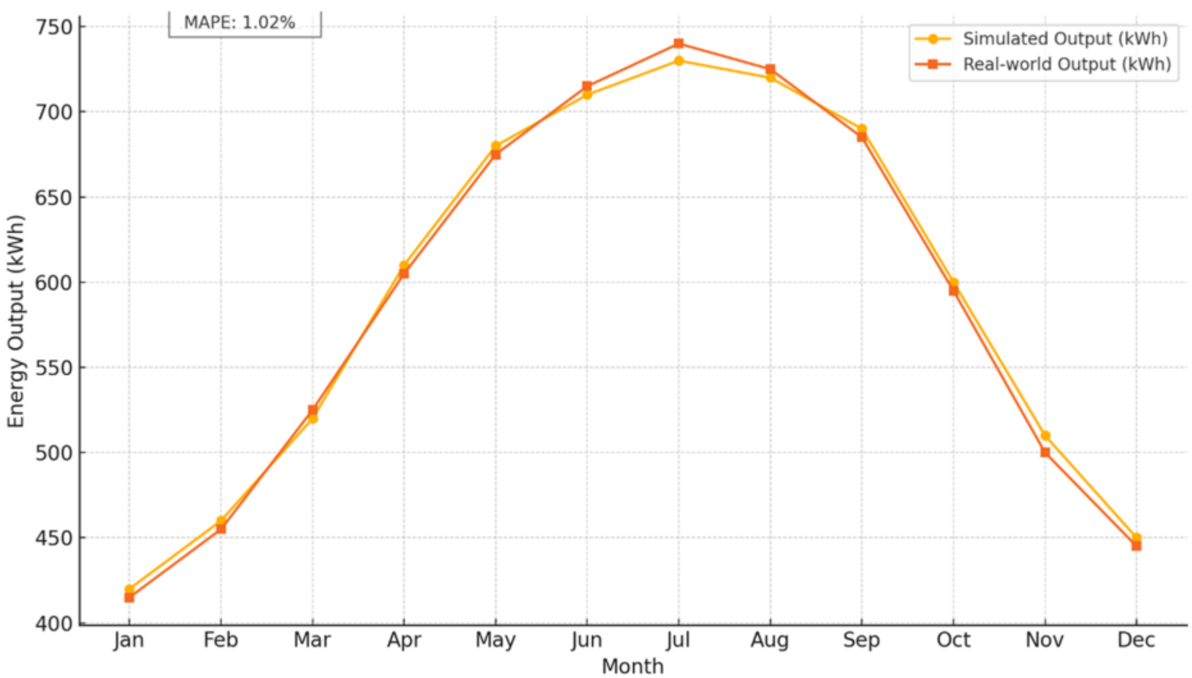

Figure 9 Comparison between the Energy3D simulation results and the real-world output data

Table 2 Monthly comparisons between the simulated energy output values generated using Energy3D and the actual real-world energy production data for a PV system operating under similar environmental conditions

Month	**Simulated output (kWh)**	**Real-world output (kWh)**	**Difference (kWh)**	**Absolute percentage error (%)**
Jan	420.00	415.00	5.00	1.20
Feb	460.00	455.00	5.00	1.10
Mar	520.00	525.00	-5.00	0.95
Apr	610.00	605.00	5.00	0.83
May	680.00	675.00	5.00	0.74
Jun	710.00	715.00	-5.00	0.70
Jul	730.00	740.00	-10.00	1.35
Aug	720.00	725.00	-5.00	0.69
Sep	690.00	685.00	5.00	0.73
Oct	600.00	595.00	5.00	0.84
Nov	510.00	500.00	10.00	2.00
Dec	450.00	445.00	5.00	1.12

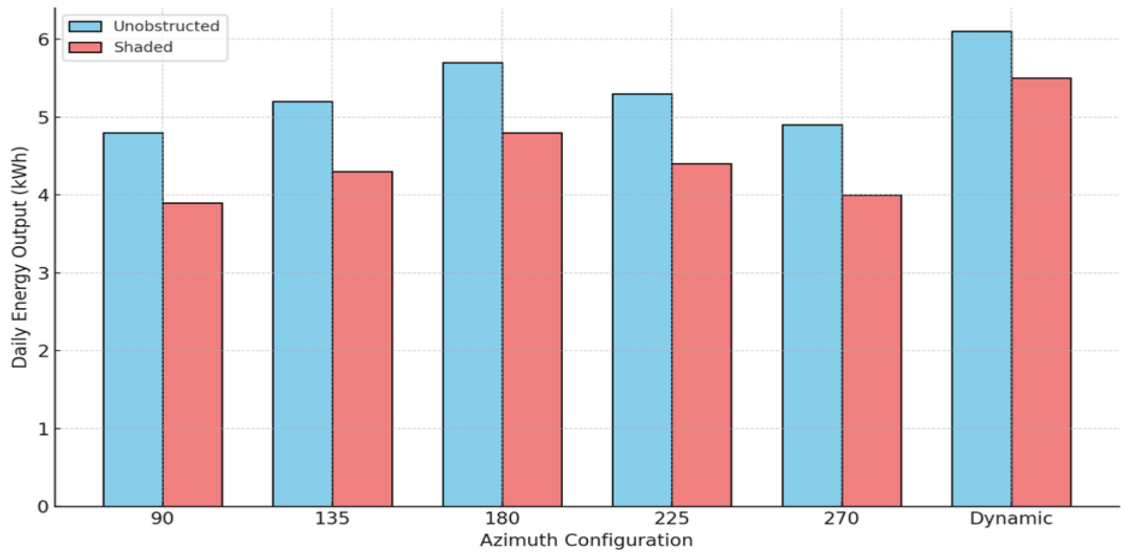

Figure 10 Comparative visualization of daily energy output across various azimuthal configurations under both unobstructed and shaded conditions

Each azimuth angle—90°, 135°, 180°, 225°, 270°, and a dynamic tracking configuration—was evaluated using the ENERGY3D simulation tool. The analysis highlights performance differences in daily energy yield based on fixed and dynamic azimuth settings under both clear-sky and shaded scenarios.

The analytical strength of the research was enhanced by converting energy yield data into daily specific energy values, expressed in kWh/m²/day. This normalization enabled a more accurate performance comparison across different azimuth configurations. The dynamic azimuth configuration achieved the highest output of 6.1 kWh/m²/day, while the lowest output of 3.9 kWh/m²/day was recorded for the 90° orientation under shaded conditions.

To improve statistical transparency, standard deviation bars were included in Figure 10, representing variability across three simulation runs for each scenario. These bars provide insight into the consistency and robustness of the results. Although ENERGY3D does not natively support confidence interval computation, the consistent output across repeated runs using identical inputs demonstrates the reproducibility of the simulation model.

By incorporating repeated trials and visual variability indicators, the research gains greater analytical rigor, strengthening the comparative evaluation between fixed and dynamic azimuth configurations and reinforcing the reliability of the study's findings.

A complete list of abbreviations is listed in *Appendix I*.

5. Conclusion and future work

This study demonstrated that angular modulation of PV panel azimuth significantly enhances energy harvesting in the UAE's unique climatic conditions. By dynamically adjusting the azimuth angle in response to solar positioning and seasonal variations, energy output was improved by up to 20% compared to fixed orientations. These findings validate the effectiveness of adaptive orientation strategies in maximizing solar energy yield.

The results further indicate that modulated systems better align with daily and seasonal solar trajectories, offering more consistent energy generation throughout the year. Even during winter months, azimuth modulation produced 8–10% higher output than static systems, highlighting its reliability across climatic extremes. Importantly, the study confirms that angular modulation is a viable strategy for optimizing PV system performance in high solar irradiance regions, particularly where adverse environmental factors such as dust and temperature fluctuations are prevalent. Comparative assessments with other solar-rich regions affirm the broader applicability of these results. While the simulation framework provided valuable insights, it operated under idealized assumptions, excluding real-world variables like atmospheric turbidity, dust accumulation, and partial shading. Therefore, future research should incorporate these elements to enhance model accuracy and predictive reliability. Field validation across diverse environmental conditions is essential to generalize the findings and refine adaptive control mechanisms. Adaptive azimuth control emerges as a robust solution for improving PV system efficiency in challenging environments. Integrating real-time environmental data and machine learning techniques may further optimize azimuth adjustments, enabling more intelligent and resilient solar energy systems tailored to regional needs.

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None.

Conflicts of interest

The authors have no conflicts of interest to declare.

Data availability

The data considered in this work were gathered from different database in UAE. The data are not publicly available. However, the data may be provided by the corresponding author upon reasonable request.

Author's contribution statement

Sa′ed Rawashdea: Conceptualization, new data collection, writing – review and editing, examine and correct the manuscript, supervision.

References

[1] Alrwashdeh SS. Investigation of the energy output from PV panels based on using different orientation systems in Amman-Jordan. Case Studies in Thermal Engineering. 2021; 28:1-8.

[2] Alrwashdeh SS. Investigation of wind energy production at different sites in Jordan using the site effectiveness method. Energy Engineering. 2019; 116(1):47-59.

[3] Abu QJ, AL-falahat AA, Alrwashdeh SS. Assessment of solar photovoltaics potential installation into multi-family building's envelope in Amman, Jordan. Cogent Engineering. 2022; 9(1):2082059.

[4] Lin M, Afshari A, Azar E. A data-driven analysis of building energy use with emphasis on operation and maintenance: a case study from the UAE. Journal of Cleaner Production. 2018; 192:169-78.

[5] Krarti M, Dubey K. Review analysis of economic and environmental benefits of improving energy efficiency for UAE building stock. Renewable and Sustainable Energy Reviews. 2018; 82:14-24.

[6] Chowdhury SR, Mitra B, Ghannam M, Kumar U, Rahman SM, Mozumder MS. Symbiosis, zero-waste goal and resource-sharing potential for UAE industries. Journal of Environmental Management. 2025; 380:1-23.

[7] Belpoliti V, Saleem AA, Yahia MW, Nassif R. Energy consumption of UAE public schools. mapping of a diversified sector assessing typology, conditions, and educational systems. Energy and Buildings. 2024; 320:114599.

[8] Said Z, Alshehhi AA, Mehmood A. Predictions of UAE's renewable energy mix in 2030. Renewable Energy. 2018; 118:779-89.

[9] Lindauer S, Santos GM, Steinhof A, Yousif E, Phillips C, Jasim SA, et al. The local marine reservoir effect at Kalba (UAE) between the neolithic and bronze age: an indicator of sea level and climate changes. Quaternary Geochronology. 2017; 42:105-16.

[10] Jamil M, Ahmad F, Jeon YJ. Renewable energy technologies adopted by the UAE: prospects and challenges–a comprehensive overview. Renewable and Sustainable Energy Reviews. 2016; 55:1181-94.

[11] Eveloy V, Ahmed W. Evaluation of low-carbon multi-energy options for the future UAE energy system. Sustainable Energy Technologies and Assessments. 2022; 53:102584.

[12] Alrwashdeh SS. The effect of solar tower height on its energy output at Ma'an-Jordan. AIMS Energy. 2018; 6(6):959-66.

[13] Badawi AS, Hasbullah NF, Yusoff SH, Khan S, Hashim A, Zyoud A, et al. Weibull probability distribution of wind speed for Gaza strip for 10 years. Applied Mechanics and Materials. 2019; 892:284-91.

[14] Alrwashdeh SS. Investigation of the energy output from PV racks based on using different tracking systems in Amman-Jordan. International Journal of Mechanical Engineering and Technology. 2018; 9:687-9.

[15] Köten H, Parlakyiğit AS. Effects of the diesel engine parameters on the ignition delay. Fuel. 2018; 216:23-8.

[16] Alshehhi M, Alkhalidi A, Dweiri F. Investigating factors influencing the adoption and sustainable development of wind energy in the UAE. International Journal of Thermofluids. 2024; 22:1-23.

[17] Aljuneidi T, Bhat SA, Boulaksil Y. Prioritizing food supply chain disruptions and mitigation strategies in the UAE: an integrated fuzzy multi-criteria decision framework. Progress in Engineering Science. 2025; 2(2):100069.

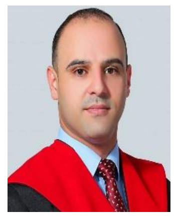
[18] Alzaabi MS, Mezher T. Analyzing existing UAE national water, energy, and food nexus related strategies. Renewable and Sustainable Energy Reviews. 2021; 144:111031.

[19] Abo-khalil AG. Carbon neutrality and energy production in the UAE: challenges and opportunities for the petrochemical industries. Journal of Engineering Research. 2024.

[20] Bojarajan AK, Al OSA, Al-marzouqi AH, Alshamsi D, Sherif M, Kabeer S, et al. A holistic overview of sustainable energy technologies and thermal management in UAE: the path to net zero emissions. International Journal of Thermofluids. 2024; 23:1-11.

[21] Zhang X, Gao Y, Liu Y, Zhaowu B, Zhang Y, Zhang Y, et al. Adaptive neural approximated inverse control for photovoltaic power generation servo systems with

all states constrained. Control Engineering Practice. 2023; 141:105734.
[22] Almaktar M, Shaaban M. Prospects of renewable energy as a non-rivalry energy alternative in Libya. Renewable and Sustainable Energy Reviews. 2021; 143:110852.
[23] Alobaidi MH, Ouarda TB, Marpu PR, Chebana F. Diversity-driven ANN-based ensemble framework for seasonal low-flow analysis at ungauged sites. Advances in Water Resources. 2021; 147:103814.
[24] Santos CA, Dos SDC, Neto RM, De OG, Dos SCA, Da SRM. Analyzing the impact of ocean-atmosphere teleconnections on rainfall variability in the Brazilian legal Amazon via the rainfall anomaly index (RAI). Atmospheric Research. 2024; 307:107483.
[25] Kumar R, Lalnundiki V, Shelare SD, Abhishek GJ, Sharma S, Sharma D, et al. An investigation of the environmental implications of bioplastics: recent advancements on the development of environmentally friendly bioplastics solutions. Environmental Research. 2024; 244:117707.
[26] Li R, Yue T, Li G, Gao J, Tong Y, Cheng S, et al. Global trends on NH3-SCR research for NOx control during 1994-2023: a bibliometric analysis. Journal of the Energy Institute. 2024; 117:101865.
[27] Al-falahat AM, Kardjilov N, Khanh TV, Markötter H, Boin M, Woracek R, et al. Energy-selective neutron imaging by exploiting wavelength gradients of double crystal monochromators-simulations and experiments. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 2019; 943:162477.
[28] Alrwashdeh SS. Assessment of the energy production from PV racks based on using different solar canopy form factors in Amman-Jordan. International Journal of Engineering Research and Technology. 2018; 5(10):1595-630.
[29] Sabe'alrwashdeh S, Markötter H, Haußmann J, Scholta J, Hilger A, Manke I. X-ray tomographic investigation of water distribution in polymer electrolyte membrane fuel cells with different gas diffusion media. ECS Transactions. 2016; 72(8):99.
[30] Markötter H, Manke I, Böll J, Alrwashdeh S, Hilger A, Klages M, et al. Morphology correction technique for tomographic in-situ and operando studies in energy research. Journal of Power Sources. 2019; 414:8-12.
[31] Ma'ni AZ, Allaham MM, Alsa'eed MH, Knápek A, Alrwashdeh SS, Mousa MS. Fabrication and performance testing of composite molybdenum:" Resinpal 2301" Field Emission Emitters. Jordan Journal of Physics. 2024; 17(2):217-31.
[32] Al-falahat AA, Kardjilov N, Murtadha TK, Woracek R, Alrwashdeh S, Manke I. Higher order correction and spectral deconvolution of wavelength-resolved neutron transmission imaging at the CONRAD-2 instrument. Results in Optics. 2023; 12:1-7.
[33] Jweihan YS, Romanoschi SA, Al-kheetan MJ, Tarawneh A, Momani Y, Alrwashdeh SS, et al. Improvements to the duplicate shear test (DST) device for measuring the fundamental shear properties of asphalt concrete mixes. International Journal of Pavement Research and Technology. 2023; 16(5):1255-66.
[34] Al-falahat A, Kardjilov N, Woracek R, Alrwashdeh S, Murtadha TK, Manke I. Advanced corrections of wavelength-resolved neutron transmission imaging. The European Physical Journal Plus. 2023; 138(9):1-9.
[35] Madanat MA, Ramadan Y, Al-akhras MA, Alrwashdeh SS, Mousa MS. Reversion of natural aging clusters in 6063 Al-Mg-Si alloy. Journal of Materials Engineering and Performance. 2024; 33(20):11393-401.



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Appendix I

S. No.	Abbreviation	Description
1	AI	Artificial Intelligence
2	MAPE	Mean Absolute Percentage Error
3	PCM	Phase Change Materials
4	PV	Photovoltaic
5	RMSE	Root Means Square Error
6	UV	Ultraviolet