

Smart evaporative cooling for photovoltaic panels: Enhancing solar-powered irrigation performance in arid regions

Laith Akeelaldeen Zeinaldeen¹, John D. Reeve², Łukasz Adam Gierz^{3*}

¹ Department of Agricultural Machines and Equipment, College of Agricultural Engineering Sciences, University of Baghdad, Al-Jadriya Campus, 10071 Baghdad, Iraq

² Department of Zoology, College of Biological Sciences, Southern Illinois University, 1263 Lincoln Drive, Mail Code 6501, Carbondale, IL 62901, USA

³ Institute of Machine Design, Faculty of Mechanical Engineering, Poznan University of Technology, Piotrowo 3, 60-965 Poznań, Poland

* Corresponding author's e-mail: lukasz.gierz@put.poznan.pl

ABSTRACT

Agricultural activity in arid regions faces critical challenges due to water scarcity, energy instability, and thermal degradation of photovoltaic (PV) cells that power irrigation systems. This study introduces a smart evaporative cooling system integrated directly into irrigation infrastructure, combining dynamic panel positioning with real-time sensor feedback to mitigate heat-induced efficiency losses. Unlike conventional passive cooling, the proposed design leverages evaporative cooling from irrigation basins in hyper-arid climates, offering both technical and environmental benefits. A three-year factorial experiment (2023–2025) in Baghdad, Iraq, compared monocrystalline and polycrystalline PV modules in five cooling configurations. The results demonstrated that the D cooling structure (dynamic adjustment) paired with monocrystalline panels achieved a peak power output of 144.02 W and a fill factor of 0.78, representing a 32.7% increase in maximum power and a 33.6% reduction in system power cost compared to the uncooled controls. Total energy generation improved by 439.5%, while CO₂ emissions were reduced by 93% compared to diesel-powered irrigation. This work highlights the novelty of integrating evaporative cooling with adaptive positioning for solar irrigation in extreme climates. Comparative analysis confirms that monocrystalline modules benefit more strongly from cooling interventions, though both of PV types show substantial gains. The findings establish smart evaporative cooling as a scalable pathway for sustainable agriculture, with future research prospects that include integration with bifacial PV modules, predictive machine learning models, and expansion to larger irrigation networks.

Keywords: smart cooling, solar irrigation, arid climate, PV efficiency, CO₂ reduction, dynamic adjustment.

INTRODUCTION

Water scarcity and energy insecurity continue to constrain agricultural productivity in arid and semi-arid regions, where irrigation commonly depends on diesel generators or unstable electrical grids. These systems are associated with high operating costs and significant greenhouse gas emissions [1, 2]. The rising economic burden and environmental impacts of fossil fuels have accelerated interest in renewable energy, especially solar power [3]. Solar-powered irrigation

systems offer a sustainable alternative by using abundant sunlight to support water delivery while reducing carbon dioxide emissions [4, 5]. In this broader renewable-energy context, recent studies have also highlighted the growing importance of photovoltaic systems and their integration with other renewable sources, such as wind power, to improve system reliability and energy balancing [6]. Lifecycle assessments reveal key distinctions: monocrystalline silicon photovoltaic panels produce up to 44 grams of carbon dioxide equivalent per kilowatt hour, while polycrystalline types

average 55.1 grams of carbon dioxide equivalent per kilowatt hour [7]. However, in scorching environments, photovoltaic panels lose effectiveness from excess heat, which diminishes cell voltage [8, 9]. Typically, these panels transform only 13–20% of incoming solar energy into power, releasing the balance as heat shaped by elements such as wind movement [10]. Rising heat buildup raises surface temperatures and hampers output. Evidence indicates that efficiency drops by 0.4 to 0.5% for every 1-degree Celsius rise above standard test conditions, causing major losses in desert environments and accelerating long-term degradation [11, 12], which ultimately threatens system reliability and lifespan [13].

Wind flow acts as an essential natural cooling aid; lab work revealed panels in calm conditions hitting 65 degrees Celsius with less than 10% efficiency, but 5 meters per second breezes drop temperatures by 15 degrees Celsius for 2–3% gains, and 10 meters per second achieve 20 degrees Celsius drops with 4–5% improvements [14]. Iraqi outdoor tests validated this, as 2–4 meters per second winds cooled surfaces by 10 degrees Celsius and lifted efficiency by 2% [15]. Additional data show 1 meters per second changes that yield 7 degrees Celsius relief [16], and simulations confirm 5–7 meters per second directed flows with vented sinks improve heat removal and performance by up to 4% [17, 18]. Beyond airflow, bi-facial modules have been shown to significantly increase photovoltaic efficiency by harnessing reflected irradiance, offering system-level gains when combined with cooling strategies [19]. Advanced cooling strategies ranging from passive and active systems to hybrid systems offer further performance recovery, including enhanced natural convection [20], heat sinks, water spraying, and phase change materials [21, 22]. Although water-based cooling delivers the greatest efficiency gains, passive cooling approaches continue to offer scalability and economic viability [23]. Similarly, [24] emphasized that liquid cooling yields the greatest recovery, but requires higher maintenance. In hyper arid climates, porous media cooling has been identified as a viable balance between economic feasibility and efficiency [25]. Field trials affirm that effective cooling enhances output; for example, [26] achieved 14% gains using water cooling. A hybrid cooling configuration was shown to lower panel temperatures by as much as 24 °C (approximately 40%) while simultaneously boosting energy output by 13% [27]. Furthermore, airflow-assisted

cooling can improve PV thermal behavior by more than 80% compared to ground-mounted setups [28, 29]. Nanofluid-based cooling, such as zinc oxide and aluminum oxide suspensions, has also shown notable improvements in thermal regulation and efficiency recovery [30]. Solar-powered irrigation offers a promising solution [31, 32]. Cooling integration into these frameworks shrinks system scale and costs [33, 34]. Variables such as irradiance and maximum PV voltage critically influence pumping efficiency, with panel improvements that increase pump efficacy [35, 36].

This study introduces a smart evaporative cooling system integrated directly into the irrigation infrastructure, combining dynamic panel positioning with real-time sensor feedback. The system adaptively adjusts the elevation of photovoltaic panels (PV) above irrigation basins in response to continuous measurements of panel temperature and wind velocity, improving cooling performance while maintaining structural stability under environmental loads. Unlike previous passive cooling approaches, our design actively utilises evaporative cooling from irrigation basins in hyperarid climates, delivering both technical (higher photovoltaic efficiency, reduced thermal stress) and environmental (more efficient water use, synergy with irrigation) benefits [37]. The design is embedded within an Internet of Things (IoT) framework: distributed sensors and actuator networks enable real-time monitoring and control [38, 39], while predictive analytics - using machine learning models such as XGBoost to forecast next day photovoltaic output from meteorological data - support proactive energy and water management for agricultural and recreational facilities [40, 41].

MATERIALS AND METHODS

Study area and environmental conditions

The experimental study was conducted in Baghdad, Iraq (Latitude: 33°18'55"N, Longitude: 44°21'58"E), a region characterized by a BWh (Hot Desert) climate under the Köppen-Geiger classification. Data collection spanned from May to September during 2023–2025, capturing the most severe periods of thermal stress where ambient temperatures frequently exceeded 45 °C. During the testing windows, the site recorded an average ambient temperature of 49.8 °C and a mean relative humidity of 36.1%.

Instrumentation

Performance analysis

I-V curve tracing; To track the I-V curve of solar panels, a PROVA-200 solar module analyzer manufactured by TES Electrical Electronic Corp., Taipei, Taiwan. Measurement accuracy: $\pm 1\%$ of the reading plus ± 9 mV for voltage and $\pm 1\%$ of the reading plus ± 0.9 mA for current (depending on range).

Solar irradiance measurement: To measure the intensity of solar radiation, a TES-132 solar energy meter manufactured by TES Electrical Electronic Corp., Taipei, Taiwan. Measurement precision: generally, within ± 10 W/m² or $\pm 5\%$ of reading, whichever is greater, with additional temperature-induced error of ± 0.38 W/m²/°C from 25 °C.

Solar irrigation pump; For irrigation, a 200 W solar pump (LSPI-12-20-2.5-200-1) manufactured by Zhejiang Binter Electric Machinery Co., Ltd., Zhejiang, China. Maximum capacity: 2.5 m³/h.

Experimental design and statistical framework

A 2×5 full factorial experimental design was implemented to evaluate the interaction between photovoltaic technology and mounting/cooling configurations. Factor A (PV Technology): Monocrystalline (Mono-Si), Shenzhen Sako Solar Co., Ltd., Shenzhen, Guangdong, China. and polycrystalline (Poly-Si), Lowenergie, Lowenergie Ltd., United Kingdom. Factor B (Cooling Configuration): Five levels, including a control (H0: ground mounted / uncooled), three static heights (H1: 15 cm; H2: 25 cm; H3: 35 cm), and a dynamic adjustment level (D).

Sampling and replication

To ensure statistical significance and reproducibility, each treatment combination was sampled sixteen times a day at 10-minute intervals (12:00 p.m. to 2:30 p.m.) during the peak heating

months. Data points for parameters like open-circuit voltage (V_{oc}) and short-circuit current (I_{sc}) etc. represent the mean of these daily measurements. This protocol yielded 40 replicates per combination ($N = 400$ annually). During the three-year experimental period, a total of 1200 observations were recorded (Table 1).

Statistical analysis

Data were processed using IBM SPSS Statistics (v. 27) [42]. A two-way Analysis of Variance (ANOVA) under a Randomized Complete Block Design (RCBD) was applied at a significance level of $\alpha = 0.05$. Post hoc analyzes included Tukey's HSD for within-factor interactions and Dunnett's test to compare treatments against the H0 control [43]. The effects sizes were quantified using partial eta squared (η_p^2). The linear correlations among all the metrics of the experiment were quantified using Pearson correlation coefficients.

PV-cooling structures and geometry

Photovoltaic panels were mounted on top of a field water basin with 3 meters' length, 2.5 meters width, 1 meter height, and a capacity 7.5 m³. to ensure effective cooling to enhance natural convection and reduce the temperature during Baghdad's arid summer climate, taking advantage of evaporative effects and water proximity to water to mitigate panel operation temperature as a result of the high ambient temperatures. The experimental design employed a two-factor factorial arrangement: photovoltaic module type (monocrystalline silicon [Mono-Si] and polycrystalline silicon [Poly-Si]) with (150 W) as the maximum power for both panel types, and mounting height (five levels: H0 representing control treatment was mounted directly on the ground surface to establish a baseline, H1 at 15 cm, H2 at 25 cm, H3 at 35 cm, and a dynamic adjustment level [D] that relates to real-time PV panel operation temperature and the wind velocity) (Figure 1). All PV panels were

Table 1. A summary table for the factorial design

Factor	Levels	Descriptions
A: PV Technology	2	Monocrystalline (Mono-Si), Polycrystalline (Poly-Si)
B: Mounting height	5	H0 (Ground), H1 (15 cm), H2 (25 cm), H3 (35 cm), D (Dynamic)
Replications	40	1 daily mean measurements (from 16 daily) measurements $\times$ 8 days per month $\times$ 5 months
Total sample (N)	1200	$2 \times 5 \times 40 \times 3$ (Years) = 1200 observations

south facing at a fixed tilt of 33° [44] to maximize summer solar harvest in the Baghdad climate.

“Mono-Si and Poly-Si technologies were selected as they currently represent more than 90% of the global PV market share, ensuring that the findings are relevant to the vast majority of existing solar irrigation installations.”

Hardware and control architecture

The system uses an Arduino-based connected to a high-torque linear actuator. The “D” state is not a static height but a responsive positioning system that toggles between a “High” position (35 cm) to maximize convective airflow and a “Lowered” position (15 cm) to maximize the evaporative cooling effect from the water basin.

Control logic and sampling rates

The ATmega performs a sampling routine every 10 seconds ($f_s = 0.1$ Hz) to gather data from the anemometer (wind speed, W_s) and the back-surface thermistor (panel temperature, T_p). To prevent mechanical fatigue and “hunting” (rapid oscillations of the actuator), a 5-minute hysteresis timer is applied before the system can transition back to the „high” state. The dynamic adjustment system (D) for photovoltaic panels (PV) mounted over a field water basin employs passive evaporative cooling and enhanced natural convection, with vertical clearances toggling

between $H_1 = 15$ cm (lowered state) and 35 cm (raised state) to optimize thermal management and structural stability.

A closed-loop control architecture, implemented on an Arduino ATmega 2560 microcontroller (manufacturer: Arduino S.r.l., Turin, Italy), interfaces a 12 V Glideforce Medium-Duty (MD) Linear Actuator (manufacturer: Concentric International, Des Moines, Iowa, USA; measurement code: MD-100Kgf-30cm-IP66) via dual relays for bidirectional positioning, powered by PV output through an MPPT charge controller (manufacturer: EPEVER Technology Co., Ltd., Beijing, China; measurement code: Tracer-2210A).

Environmental monitoring utilizes a DS18B20 thermistor (manufacturer: Maxim Integrated, San Jose, California, USA; measurement code: DS18B20) with $\pm 0.5^\circ\text{C}$ accuracy on digital pin 2 (4.7 k Ω pull-up) and an I²C anemometer (manufacturer: Modern Device, Providence, Rhode Island, USA; measurement code: Wind Sensor Rev. P) with ± 0.1 m/s accuracy at address 0×66 , sampled at $f_s = 0.1$ Hz (10 s intervals).

Control logic enforces three states

Standard state (Raised): Triggered only when ($T_p \leq 25^\circ\text{C}$ AND $W_s \leq 1$ m/s), maintaining the panel at 35 cm for optimal ambient air flow.

Active cooling state (Lowered): Triggered if $T_p > 25^\circ\text{C}$. The actuator lowers the panel to 15 cm (H_1) to bring the modules into the high-humidity

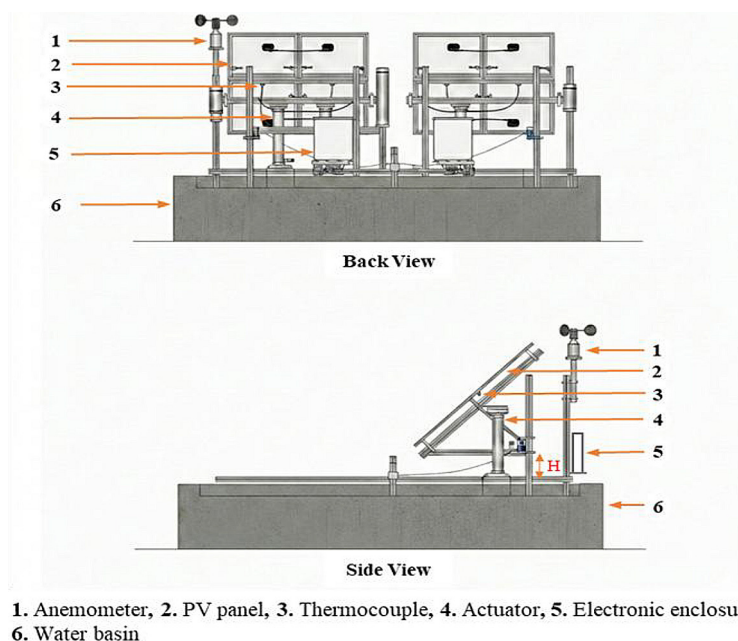


Figure 1. The experimental setup for the PV panel and the cooling structure

boundary layer immediately above the water basin, enhancing evaporative heat transfer.

Stability state (Lowered): Triggered if $W_s > 1$ m/s. The system is lower to minimize structural wind load and prevent turbulent disruption of the evaporative layer. A 300-s hysteresis timer prevents actuator fatigue and oscillatory hunting, ensuring methodological repeatability with calibrated stroke delays (~8 s at 3 mm/s) (Figure 2). The embedded routine, detailed in the Arduino firmware, guarantees robust operation compliant with specified thresholds (Table 2).

Performance indicators

The following parameters were measured:

- Maximum power output (W) – it can be defined as the maximum power that the photovoltaic panel can produce [45], Equation 1:

$$P_{max} = I_{max} \cdot V_{max} \quad (1)$$

where: P_{max} – maximum power of the PV panel (W), I_{max} – maximum current of the PV panel (A), V_{max} – maximum PV panel voltage (V).

- Fill factor (FF) – it can be defined as the ratio of maximum power to the product of short-circuit current and open-circuit voltage [46], Equation 2:

$$FF = \frac{I_{max} \cdot V_{max}}{I_{sc} \cdot V_{oc}} \quad (2)$$

where: FF – fill factor, I_{sc} – the short-circuit current (A), V_{oc} – the open-circuit voltage (V).

System power cost

It represents the net power cost of the PV – cooling system in dollars per watt, Equation 3:

$$PV_{pc} = \frac{PV_{ic}}{PV_{np}} \quad (3)$$

where: PV_{pc} – PV system power cost (\$·W⁻¹), PV_{ic} – initial cost of the PV- cooling system (\$), PV_{np} – PV system power (W).

The initial cost of the PV cooling system initial cost was calculated using Equation 4:

$$PV_{ic} = PV_{price} + Actuator_{price} + Electronic\ system_{price} \quad (4)$$

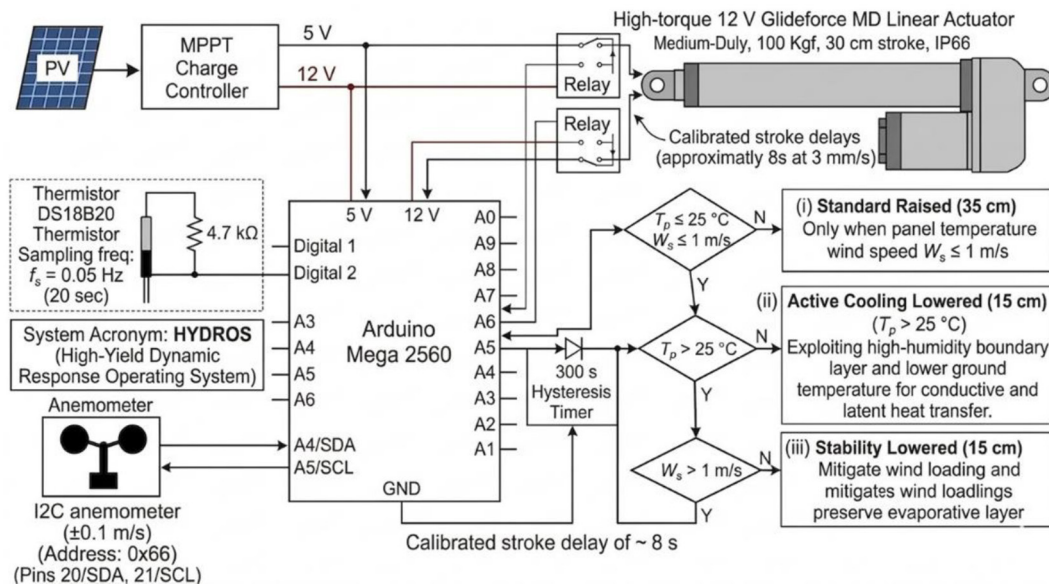


Figure 2. Integrated control architecture and logic flow for the HYDROS-A solar actuation system

Table 2. Specifications of the dynamic adjustment system

Variable	Threshold	Sensor accuracy	Sampling rate
Panel temp (T_p)	25 °C	±0.5 °C	10 s ($f_s = 0.1$ Hz)
Wind speed (W_s)	1 m/s	±0.1 m/s	10 s ($f_s = 0.1$ Hz)
Mechanical delay	300 s	N/A	Logic Control

PV system power was calculated using Equation 5:

$$PV_{np} = PV_{cp} - (PV_{ucp} + Actuator_p + ES_p) \quad (5)$$

where: PV_{cp} – cooled photovoltaic produced power (W), PV_{ucp} – uncooled PV produced power (W), $Actuator_p$ – actuator power consumed (W), ES_p – the electronic system consumed power (W).

Total energy enhancement (Wh)

It refers to the improvement in total energy output provided by each cooling mount compared to the uncooled control treatment, Equation 6:

$$E_t = E_c - (E_{uc} + E_{actuator} + E_{ES}) \quad (6)$$

where: E_t – total energy enhancement (Wh), E_c – energy produced by cooled PVs (Wh), E_{uc} – energy produced by uncooled photovoltaics (Wh), $E_{actuator}$ – energy consumed by the actuator (Wh), E_{ES} – energy consumed by the electronic system (Wh).

CO₂ emissions reduction

This represents the percentage reduction in CO₂ emissions achieved by PV panels versus a diesel generator for running the irrigation system, Equation 7:

$$CO_2 \text{ Reduction} = \frac{D_{CO_2 eq} - PV_{CO_2 eq}}{D_{CO_2 eq}} \times 100 \quad (7)$$

where: $CO_{2Reduction}$ – the percentage of reduction in CO₂ emissions (%), $D_{CO_2 eq}$ – diesel generator CO₂ emissions (g. kWh⁻¹), equation 8, $PV_{CO_2 eq}$ – CO₂ emissions from the PV panel (g), for poly-Si = 50.1 g, mono-Si = 40 g [7].

CO₂ emissions from the diesel generator were calculated using Equation 8:

$$D_{CO_2 eq} = F_c \times EF_{CO_2} \quad (8)$$

where: $D_{CO_2 eq}$ – CO₂ emissions from the diesel generator (g·kWh⁻¹), F_c – fuel consumption average ≈ 0.26 L/kWh, EF_{CO_2} – CO₂ emission factor for diesel, typically = 2.7 kg/L [47].

RESULTS AND DISCUSSION

Electrical performance of photovoltaic panels

Maximum power

The Two-Way ANOVA results (Table 3) indicate that both PV Type and Cooling Structure, as well as their interaction, have a statistically significant effect on the maximum power output ($p < 0.001$). The Cooling Structure emerged as the most influential factor, accounting for approximately 86% of the variance in power ($F_{(4,1190)} = 2125.04$, $p < 0.001$, $\eta_p^2 = 0.86$), illustrating its dominant role in mitigating thermal losses. While PV type explained roughly 57% of the variance ($F_{(1,1190)} = 1888.90$, $p < 0.001$, $\eta_p^2 = 0.57$). Crucially, the significant interaction effect between the two ($F_{(4,1190)} = 105.78$, $p < 0.001$, $\eta_p^2 = 0.23$) suggests that the impact of a specific cooling method is not uniform across different panel types; rather, the optimal cooling configuration depends on the PV material is being used. Our findings are consistent with those of [26], who reported that combined cooling systems (water sprinklers and air fans) significantly improved PV efficiency, with cooling emerging as the dominant factor in performance enhancement. Similarly, [24] demonstrated through thermal–electrical modeling that air, water, and porous media cooling methods substantially mitigate thermal losses, supporting our conclusion that the cooling structure is the primary determinant of power output. The strong interaction effect between photovoltaic type and cooling structure aligns with [11], who

Table 3. Two-way analysis of variance results for PV type and cooling structure on PV panel maximum power (W)

Source	Sum of squares	df	Mean square	F	Sig.	Partial eta squared
PV type	59486.51	1	59486.51	1888.90	0.000	0.57
Cooling structure	267693.09	4	66923.27	2125.04	0.000	0.86
PV type * cooling structure	13324.68	4	3331.17	105.78	0.000	0.23
Error	45034.65	1190	37.84			
Total	385538.93	1199				

emphasized that monocrystalline cells are more thermally sensitive than polycrystalline ones, thus benefiting disproportionately from cooling interventions.

However, divergence arises when compared to [14], who found that air velocity alone produced notable improvements in photovoltaic performance under controlled laboratory conditions. In our study, while convective cooling contributed, the dominant mechanism was evaporative cooling from the water basin. This discrepancy may be explained by environmental differences: Ali et al. tested in moderate climates, whereas our system operated in an arid summer, where evaporative cooling is more effective due to low humidity. This climate dependence is echoed by [16], who highlighted that wind-induced cooling effects vary significantly depending on the rooftop installation environment.

Monocrystalline panels combined with the cooling structure D achieved the highest maximum power output (144.024 W) (Figure 3) with a significant interaction effect ($p < 0.001$), demonstrating a higher thermal sensitivity than polycrystalline modules (121.03 W), suggesting that advanced cooling is more ecologically and technically efficient when combined with high-efficiency cell materials.

Post hoc comparisons using Tukey's HSD test showed highly significant differences between all treatments ($p < 0.001$). Dunnett's test confirmed highly significant differences between H0 and all other treatments (D, H1, H2, H3; all $p < 0.001$) for maximum PV power.

Fill factor

A two-way analysis of variance (Table 4) illustrates the effects of the type of photovoltaic (PV) and cooling structure on fill factor (FF).

The results indicated that both photovoltaic technology and the cooling structure had highly significant effects on the fill factor ($p < 0.001$). The type of photovoltaic was highly significant ($F_{(1,1190)} = 967.65$, $p < 0.001$, $\eta_p^2 = 0.40$), with monocrystalline cells consistently outperformed polycrystalline variants across all cooling conditions. Similarly, the configuration of the cooling structure significantly modulated the electrical performance ($F_{(4,1190)} = 665.45$, $p < 0.001$, $\eta_p^2 = 0.65$).

The present study revealed a highly significant interaction between the cooling structure of type PV type $\times$ Cooling structure ($F_{(4,1190)} = 137.44$, $p < 0.001$, $\eta_p^2 = 0.28$), underscoring that the cooling benefit is strongly dependent on the semiconductor substrate. As shown in Figure 4, monocrystalline modules achieved the highest fill factor (FF = 0.78) in cooling structure D, compared to the baseline H0 configuration (FF = 0.59). Polycrystalline modules followed a similar but attenuated trend, with structure D yielding a mean FF of 0.67. These findings confirm that advanced passive cooling is particularly effective for high-efficiency photovoltaic technologies, improving critical indicators such as fill factor. Our results agree with those of [10], who showed that increasing the temperature reduces PV performance, particularly in monocrystalline cells. The improvement with

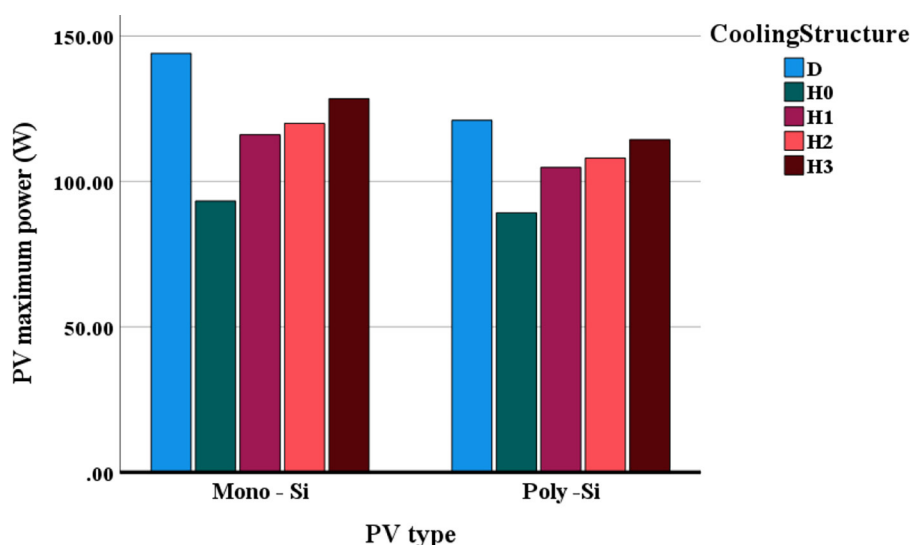


Figure 3. Effect of PV type and cooling structure on PV maximum power (W)

Table 4. Two-way analysis of variance results for PV type and cooling structure on PV panel fill factor

Source	Sum of squares	df	Mean square	F	Sig.	Partial eta squared
PV type	0.96	1	0.96	967.65	0.000	0.40
Cooling structure	2.64	4	0.66	665.45	0.000	0.65
PV type * cooling structure	0.54	4	0.14	137.44	0.000	0.28
Error	1.42	1190	0.00			
Total	5.55	1199				

cooling structure D supports their conclusion that thermal management is vital for sustaining efficiency. Similarly, [27] found that combined cooling systems enhanced module efficiency, consistent with our observation that integrated cooling geometries are most effective.

On the contrary, [14] reported that air velocity alone significantly improved photovoltaic efficiency under controlled conditions. Our study, conducted in Baghdad's arid climate, found evaporative cooling more dominant, reflecting climatic differences. This dependency is reinforced by [16], who noted variability in wind-induced cooling across rooftop environments. Finally, the weaker response of polycrystalline modules aligns with [13], who highlighted reduced thermal resilience due to optical and material degradation. Thus, while both PV types benefit from cooling, monocrystalline modules show stronger gains, consistent with [45].

Tukey's test showed significant differences among all treatments ($p < 0.001$). Dunnett's test confirmed significant differences between H0 and all other treatments (D, H1, H2, H3; all $p < 0.001$) for PV fill factor. The mean difference between D

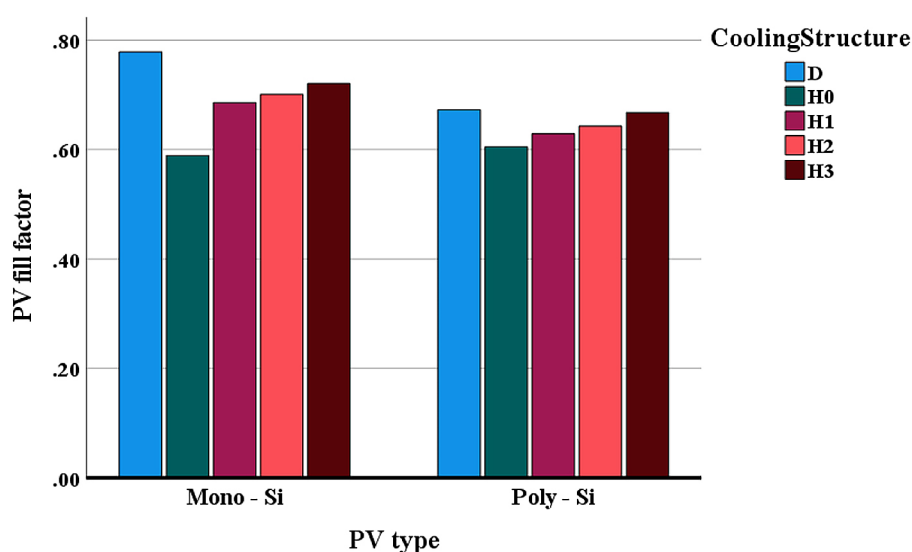
and H0 was 0.13 ($p < 0.001$), indicating that structural design is crucial for improving PV thermal management and stabilizing fill factor.

Economic viability

System power cost

A two-way analysis of variance (Table 5) reveals that both the PV type and the cooling structure, as well as their interaction, have a statistically significant impact ($p < 0.001$) on the power cost ($\$/W^{-1}$).

The cooling structure is the most dominant factor, boasting a substantial F-statistic of 254.21 and a large effect size ($\eta_p^2 = 0.42$), indicating that the cooling design is a primary determinant of economic performance in this system [42]. Although the type of photovoltaic is also significant, its practical impact is much smaller ($\eta_p^2 = 0.04$). The significant interaction ($p = 0.001$) suggests that the effectiveness of a specific cooling structure depends slightly on the type used, though the near-zero effect size ($\eta_p^2 = 0.01$) implies this relationship is negligible compared to the primary


Figure 4. PV type and cooling structure effect on PV fill factor

influence of the cooling method itself. This suggests that the impact of the cooling structure on the system power cost remains consistent regardless of the type of PV utilized, allowing for a generalized application of the most efficient cooling designs across different PV technologies.

The statistical superiority of structure D ($M = 0.81$) over baseline H0 ($M = 1.22$) represents an approximately 33.6% reduction in power cost. This suggests that the heat transfer mechanism inherent in Structure D significantly enhances the electrical efficiency of the photovoltaic cells by maintaining lower operating temperatures, thus reducing thermal degradation of power output. Our findings are consistent with those of [22], who classified advanced cooling designs as the most effective strategy for maintaining photovoltaic efficiency and reducing costs. Similarly, [8] emphasized that cooling techniques directly enhance economic performance by mitigating thermal degradation. The results also align with those of [17], who demonstrated that optimized heat sink geometries significantly improve PV cooling efficiency, supporting the conclusion that

design-driven cooling outweighs material differences in economic impact. The divergence with [12], who reported high variability in photovoltaic performance under uncontrolled field conditions, may be explained by the stabilizing effect of our structured cooling system, which minimized environmental variability.

Figure 5 illustrates that the highest power results were observed in the H0 configuration, particularly for polycrystalline cells ($1.23 \$ \cdot W^{-1}$), indicating that without active or optimized cooling, the system is highly sensitive to environmental fluctuations, leading to inconsistent economic returns. In contrast, the lowest results were achieved in Structure D for Monocrystalline ($0.74 \$ \cdot W^{-1}$), suggesting that optimized cooling not only reduces cost, but also provides a more stable and predictable energy yield.

Tukey's test showed highly significant differences between control treatment (H0) and all other treatments (D, H1, H2, H3; all $p < 0.001$), as well as significant differences between several treatment pairs (all $p \leq 0.010$ except H1 vs H2). Dunnett's test (versus control H0) confirmed

Table 5. Two-way analysis of variance results for PV type and cooling structure on system power cost ($\$ \cdot W^{-1}$)

Source	Sum of squares	df	Mean square	F	Sig.	Partial eta squared
PV type	3.08	1	3.08	113.23	0.000	0.04
Cooling structure	27.69	4	6.92	254.21	0.000	0.42
PV type * cooling structure	0.51	4	0.13	4.67	0.001	0.01
Error	38.94	1190	0.03			
Total	70.21	1199				

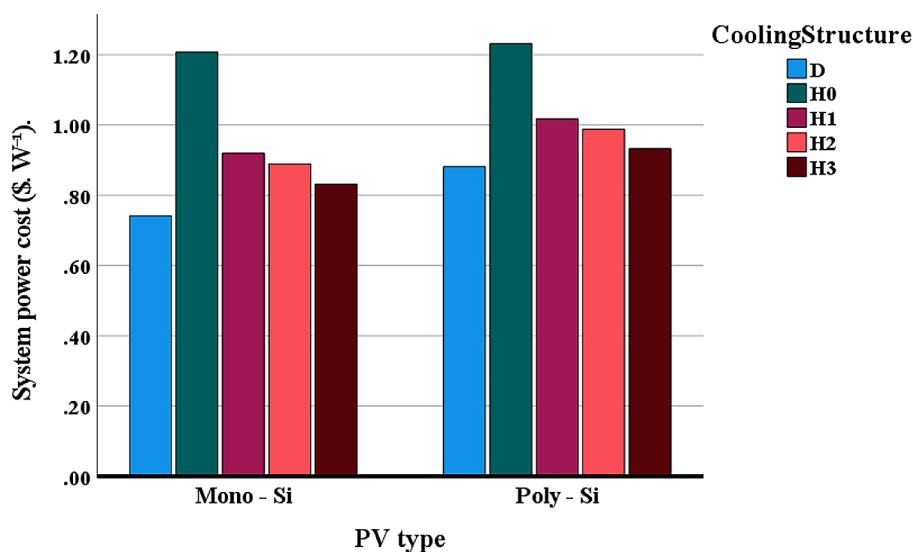


Figure 5. Effect of PV type and cooling structure on system power cost ($\$ \cdot W^{-1}$)

highly significant differences between H0 and all other treatments (D, H1, H2, H3; all $p \leq 0.004$) for PV power cost.

Sustainability

Energy enhancement

A two-way analysis of variance (Table 6) illustrates the effects of the type and cooling structure on the energy enhancement of the PV module (Wh).

A highly significant effect of the type of photovoltaic was observed on energy enhancement was observed ($F_{(1,1190)} = 485.20$, $p < 0.001$, $\eta_p^2 = 0.25$). The geometric configuration of the cooling structure is the primary driver of performance ($F_{(4,1190)} = 371.49$, $p < 0.001$, $\eta_p^2 = 0.51$). The interaction between the type of photovoltaic and the cooling structure is statistically significant ($p < 0.001$). This indicates that the efficacy of a cooling structure is nonlinearly dependent on the semiconductor material. However, the small effect size ($\eta_p^2 =$

0.03) suggests the structural impact is relatively consistent between types. Figure 6 shows that structure D has the optimal geometry for optimizing the energy yield for both semiconductor types. Structure D with monocrystalline (Mono-Si) achieves a peak energy enhancement of 50.76 Wh, outperforming the baseline H0 configuration, which suffers from a negative enhancement of 6.08 Wh. While polycrystalline (Poly-Si) modules generally exhibit lower thermal responsiveness, Structure D remains the only configuration to provide a positive gain (31.83 Wh) for this type of photovoltaic, while all H of the series structures (H0–H3) result in energy degradation ranging from -4.93 to -18.25 Wh. These results indicate a strong interaction between structure geometry and photovoltaic chemistry, suggesting that monocrystalline technology paired with Structure D represents the most robust configuration for maximizing power output and mitigating thermal losses. These results are consistent with [26, 30], who emphasized the importance of cooling geometry in hot climates. Differences observed in

Table 6. Two-way analysis of variance results for PV type and cooling structure on PV panel energy enhancement (Wh)

Source	Sum of squares	Df	Mean square	F	Sig.	Partial eta squared
PV type	150333.96	1	150333.96	485.20	0.000	0.25
Cooling structure	460411.47	4	115102.87	371.49	0.000	0.51
PV type * cooling structure	11910.52	4	2977.63	9.61	0.000	0.03
Error	443069.74	1190	372.33			
Total	1065725.69	1199				

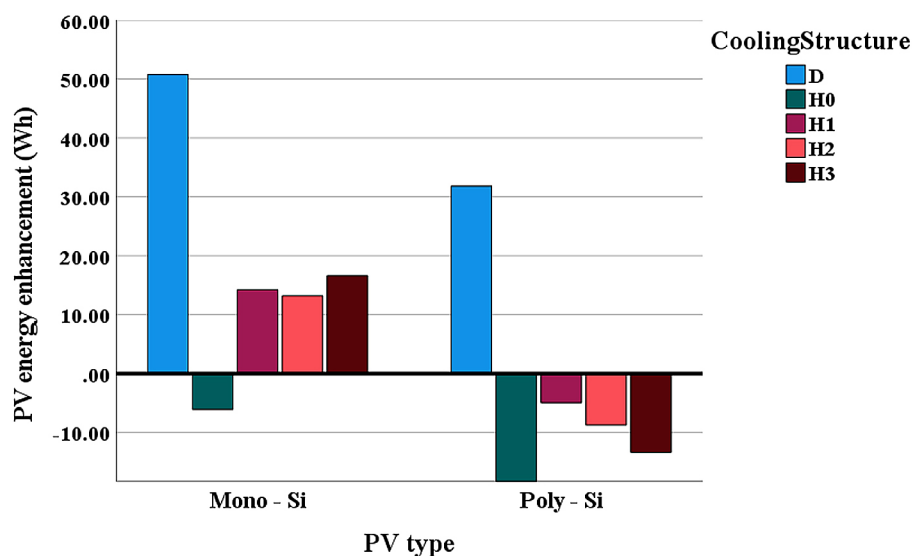


Figure 6. PV type and cooling structure effect on PV energy enhancement (Wh)

comparison with prior studies highlight the influence of uncontrolled field conditions and severe weather events, both of which can diminish or even negate the effectiveness of cooling strategies [8, 11]. The weaker polycrystalline response matches [13], who linked optical degradation to reduced thermal resilience.

Tukey's test showed highly significant differences between control treatment (H0) and all other treatments (H1, H2, H3 and D; all $p < 0.001$). Among treatments, D outperformed all others, while H1, H2, and H3 were not significantly different from each other ($p > 0.765$). Dunnett's test (versus control H0) confirmed highly significant differences between H0 and all other treatments (all $p < 0.001$) for the enhancement of PV energy.

CO₂ emissions reduction (%)

A two-way analysis of variance (Table 7) illustrates the effects of the type of PV and cooling structure on the reduction in CO₂ emissions (%).

The main effect of the type of photovoltaic was highly significant $F_{(1,1190)} = 252.34$, $p < 0.001$, $\eta_p^2 = 0.15$), confirming that the choice of cell material contributes significantly to carbon mitigation by explaining 15% of the total variance. The cooling structure exerted the most profound influence on the dependent variable ($F_{(4,1190)} = 441.75$, $p < 0.001$, $\eta_p^2 = 0.55$), with the high effect size suggesting that more than half (55%) of the variance in the reduction in CO₂ is determined by the specific cooling geometry. This highlights that thermal design is nearly four times more influential than photovoltaic material in optimizing carbon footprints. Crucially, the interaction between the type of photovoltaic and the cooling structure was also found to be statistically significant ($F_{(4,1190)} = 4.09$, $p = 0.003$, $\eta_p^2 = 0.01$). Although the small effect size indicates that the relationship is subtle, the significant p-value (0.003) actually refutes the claim that the benefits are entirely independent; instead, it suggests that the impact of the cooling structures varies slightly depending on the solar cell technology used.

As illustrated in Figure 7, the Structure D configuration consistently produced the highest mean of CO₂ reduction per kWh across both PV types, achieving a global mean of 92.83%. The H0 baseline configuration resulted in the lowest environmental mitigation ($M = 89.38\%$). These findings align with those of [7], who emphasized harmonized carbon footprint calculations showing that design factors outweigh material differences. Evidence from earlier studies indicates that geometric cooling using porous fins enhanced photovoltaic efficiency under Baghdad's climate, reinforcing the conclusion that structural design is a decisive factor in environmental performance. In addition, cooling strategies have been shown to directly mitigate emissions by reducing thermal degradation [8, 10]. Similarly, [9] noted extreme weather can override cooling benefits, while our results show stable reductions under arid conditions. The weaker polycrystalline response is consistent with [13], who linked optical degradation to reduced thermal resilience.

Tukey's test showed highly significant differences between control treatment (H0) and all other treatments (H1, H2, H3 and D; all $p < 0.001$), along with significant differences between several treatment pairs ($p \leq 0.009$ except H1 vs H2). Dunnett's test (versus control H0) confirmed highly significant differences between H0 and all other treatments (D, H1, H2, H3; all $p \leq 0.004$) for PV CO₂ reduction. Compared to the diesel generator, which produces (140.00 g/kWh), monocrystalline has the lowest mean CO₂ production, followed by polycrystalline (11.268, 12.504 g/kWh), respectively (Figure 8).

Table 8 shows that smart cooling substantially improves PV performance and sustainability compared with the uncooled case. It increases maximum power output and fill factor, while also reducing system power cost and cutting CO₂ emissions, with the gains generally stronger for the monocrystalline panel than for the polycrystalline one.

Table 7. Two-way analysis of variance results for PV type and cooling structure on PV CO₂ emissions reduction (%)

Source	Sum of squares	df	Mean square	F	Sig.	Partial eta squared
PV type	279.97	1	279.97	252.34	0.000	0.15
Cooling structure	1960.52	4	490.13	441.75	0.000	0.55
PV type * cooling structure	18.16	4	4.54	4.09	0.003	0.01
Error	1586.61	1190	1.33			
Total	3845.26	1199				

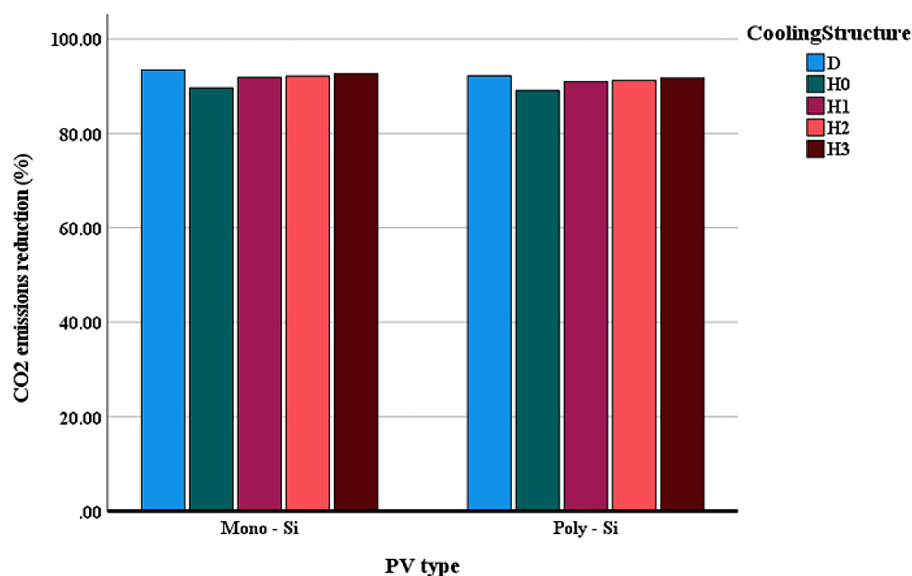


Figure 7. Effect of PV type and cooling structure on CO₂ emissions reduction (%)

The Pearson correlation coefficient analysis revealed a strong positive relationship between the fill factor and the maximum power ($r = 0.949$), confirming that electrical quality is the primary driver of PV output. This is consistent with [46], who refined empirical expressions for the fill factor and showed its direct dependence on material quality and defect density. The perfect inverse correlation between power cost and CO₂ Reduction ($r = -1.000$) suggests that economic efficiency and environmental mitigation are functionally interdependent. This aligns with [8], who emphasized that carbon footprint reductions in photovoltaic systems are closely related to operational efficiency under EU sustainability frameworks. The strong negative correlation

between maximum power and Power Cost ($r = -0.913$) demonstrates economies of scale, consistent with [11], who found that geometric cooling designs in Baghdad improved efficiency and reduced costs simultaneously. Moderate correlations involving energy enhancement ($r \approx 0.45\text{--}0.64$) indicate variable returns from supplementary techniques. This variability agrees with [31], who reported that hybrid nanoparticle cooling improved performance, but with context-dependent outcomes. Divergence is observed compared to [13], who observed high variability in photovoltaic indices under uncontrolled field conditions; our structured cooling system minimized such fluctuations, producing more predictable correlations.

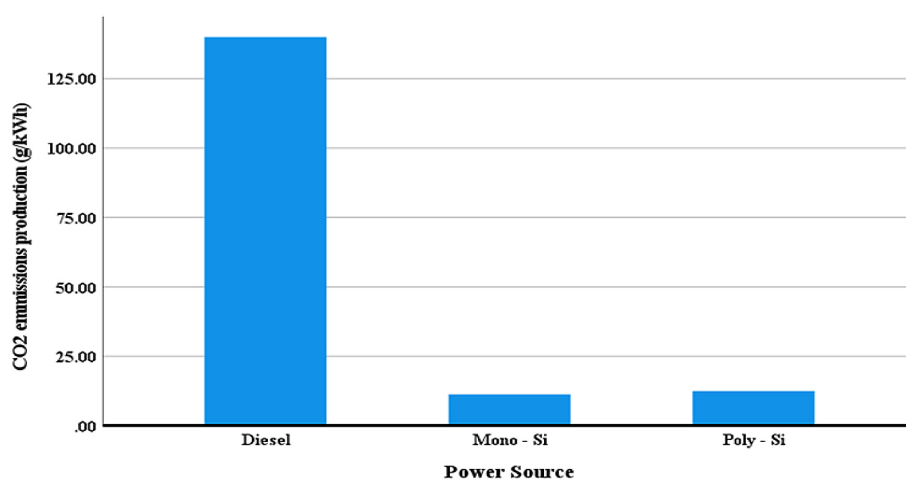


Figure 8. Effect of the power source on CO₂ emissions production (g/kWh)

Table 8. Comparative analysis of PV performance before and after cooling

Parameter	Uncooled (H0)	Smart cooling (D)	Improvement
Maximum power output (W)	108.52 (Mono-Si) 95.34 (Poly-Si)	144.02 (Mono-Si) 121.03 (Poly-Si)	+32.7% (Mono-Si) +27.0% (Poly-Si)
Fill Factor (FF)	0.59 (Mono-Si) 0.54 (Poly-Si)	0.78 (Mono-Si) 0.67 (Poly-Si)	+32.2% (Mono-Si) +24.1% (Poly-Si)
System power cost (\$·W ⁻¹)	1.22 (Mono-Si) 1.23 (Poly-Si)	0.81 (Mono-Si) 0.89 (Poly-Si)	−33.6% (Mono-Si) −27.6% (Poly-Si)
Total energy enhancement (Wh)	Baseline (0)	+439.5% (Mono-Si) +382.1% (Poly-Si)	Significant gain
CO ₂ emissions reduction (%)	0 (Diesel baseline)	93% (Mono-Si) 89% (Poly-Si)	Major environmental benefit

CONCLUSIONS

This study demonstrates that intelligent evaporative cooling integrated with dynamic panel positioning significantly enhances the performance of PV systems that power irrigation in arid climates. By coupling evaporative cooling from irrigation basins with real-time sensor feedback, the system achieved substantial improvements in both technical and environmental outcomes. Key findings include:

- Monocrystalline PV modules paired with dynamic cooling (Structure D) achieved a 32.7% increase in maximum power output and a 33.6% reduction in system power cost compared to uncooled controls.
- The fill factor improved from 0.59 to 0.78 in monocrystalline modules, confirming the strong thermal sensitivity of high-efficiency cells and their disproportionate benefit from cooling interventions.
- Total energy generation increased by 439.5%, while CO₂ emissions were reduced by 93% compared to diesel-powered irrigation systems.
- Comparative analysis confirmed that while both PV technologies benefit from cooling, monocrystalline modules show greater resilience and efficiency gains under extreme thermal stress.
- The novelty of this work lies in its integration of evaporative cooling directly into irrigation infrastructure, combined with adaptive positioning logic that balances convective airflow, evaporative heat transfer, and structural stability. This dual mechanism represents a scalable pathway for sustainable solar irrigation in hyper-arid regions.

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