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TECHNICAL ARTICLE

Comparative Techno-Economic Analysis of Novel Closed-Loop Hydronic Cooling of PV Panels in Hot and Arid Regions

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ABSTRACT

The elevated operating temperature of photovoltaic (PV) modules in hot and arid regions accelerates performance degradation, reduces electricity generation, and adversely affects long-term economic viability. This study presents a comprehensive long-term comparative thermo-economic assessment of a closed-loop hydronic PV cooling system integrated with an above-ground water tank (PV-AGWT) and a common PV system (PV-Com) under hot and arid climatic conditions of Basra, Iraq. A three-dimensional transient model was developed using COMSOL Multiphysics to evaluate the thermal and electrical performance of both systems. The numerical results were subsequently integrated with degradation, environmental, and economic models to assess long-term system performance over a 25-year project evaluation period. The results indicate that PV-AGWT system effectively reduces PV operating temperatures, leading to an average increase of 2.07% in monthly net energy output compared with PV-Com. The improved thermal regulation decreases the annual degradation rate from 1.458%/year to 1.001%/year, extending the operational lifetime from 16.5 to 24.03 years. For a 1 MWp PV power plant, the PV-AGWT system achieves an annual net power production of 1559.78 MWh, representing an increase of 27.53 MWh/year (1.80%) relative to PV-Com, while cumulative electricity generation reaches 33.80 GWh over the project lifetime. Economic analysis shows that both configurations are financially viable, with PV-AGWT system achieving a net present value of US$1.67 million, a discounted payback period of 5.49 years, and a levelized cost of energy of 0.06 US$/kWh. The findings demonstrate that integrating an above-ground water tank with a closed-loop hydronic cooling system can simultaneously improve PV thermal regulation, mitigate long-term degradation, and enhance lifetime energy and economic performance, although these benefits should be considered alongside the additional capital and O&M requirements of the cooling system.

KEYWORDS Photovoltaic (PV), Lifetime economic evaluation, Thermal energy storage, Hydrodynamic analysis, Solar cell efficiency, Cooling

1. Introduction

Global energy demand is persistently growing, prompting increased concerns over climate change and necessitating a transition to sustainable, low carbon energy systems (Kaur *et al.* 2025; Zhou *et al.* 2026). Solar photovoltaic (PV) technology has emerged as a highly promising renewable energy source due to its scalability, environmental sustainability, abundance, and the decreasing costs associated with its installation (Ali *et al.* 2025; Kishore *et al.* 2025; Sovetova *et al.* 2025). Consequently, the increasing utilization of PV systems globally enhances sustainable electricity generation and mitigates greenhouse gas emissions. Despite these advantages, operational temperature critically influences PV system performance. During operation, only part of the solar radiation is converted

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into electricity, while the remaining energy is dissipated as heat in PV module (Bukar *et al.* 2025). This heat accumulation causes an increase in PV module temperature, which lowers electrical efficiency, diminishes power output, and accelerates material degradation (Dirawi *et al.* 2026; Marinić-Kragić *et al.* 2023). PV modules may also operate beyond their standard test condition temperatures in hot and arid climates due to high ambient temperatures and intense solar irradiation, resulting in particularly large performance losses. Field investigations under harsh Iraqi climatic conditions have also demonstrated substantial long-term PV degradation, with annual degradation rates of approximately 0.91% and 2.6% reported for PV systems installed in Basrah and Baghdad, respectively (Hameed *et al.* 2024). As a result, higher operating temperatures can have a substantial influence on PV systems' energy output, operational stability, economic feasibility, and environmental impact (Dirawi *et al.* 2024; Yazdani and Yaghoubi 2021).

To mitigate thermal losses, a variety of cooling strategies have been developed and studied in recent years. Passive cooling solutions such as natural ventilation, heat sinks (Shen *et al.* 2023) and PCM systems (Weinstein *et al.* 2008) have received considerable attention due to their simplicity, low cost, and low energy consumption. However, their ability to dissipate heat is often limited, and they may be insufficient under high solar irradiance or at elevated ambient temperatures (Dwivedi *et al.* 2020; Keyhanara *et al.* 2020). Active cooling systems are more capable of removing excess heat and improving PV electrical performance. Among these approaches, water-based thermal management has been widely investigated because the relatively high heat capacity of water enables effective heat removal and stable PV temperature control (Garcia Noxpanco *et al.* 2020). In liquid-based PV/T systems, the cooling fluid is typically circulated through channels or tubes attached to the rear of the PV module, where it absorbs excess heat and reduces the module operating temperature (Garcia Noxpanco *et al.* 2020). Closed-loop hydronic cooling applies a similar heat-removal principle while recirculating the cooling water through the system and transferring the absorbed heat to a storage tank (Dirawi *et al.* 2025). Aydın et al. (2026) experimentally evaluated an active closed-loop water-based PV system containing cylindrical-shaped fins and rectangular plate fins that connected to the back surface of PV panels. The PV cooling system consisted of PV modules integrated with an aluminium absorber with fins, a heat storage tank, and a forced water circulation loop with a pump. According to the findings, the cylindrical-fin and plate-fin configurations lowered the PV temperature by about 9.30 °C and 8.91 °C, respectively, leading to increases in electrical efficiency of around 6.3% and 3.4%. Moreover, Ahmad et al. (2022) conducted an experimental study on a closed-loop mist/fog-based rear-side cooling system for PV modules under extreme hot outdoor conditions in Sharjah, UAE. The results indicated an approximately 27% reduction in maximum PV temperature and about a 16.7% improvement in power output. Generally, closed-loop cooling systems also use less water and require less maintenance than open-loop systems, making them particularly suitable for hot and arid regions where water resources may be limited.

Numerous studies have investigated the thermal and electrical advantages of water-cooled PV systems. Lowering PV operating temperatures has been proven to enhance conversion efficiency, boost yearly energy generation, and extend system lifetime. Recent utility-scale evidence from desert environments has also demonstrated the importance of incorporating long-term degradation into economic assessment, with a five-year study of a 6 MWp PV plant in the Algerian Sahara evaluating degradation alongside indicators such as NPV and LCOE (Bendaas *et al.* 2026). Nevertheless, limited research has examined the long term techno-economic feasibility of hydronic-cooled PV systems in hot and arid climatic conditions. Furthermore, the overall impacts of annual energy production, degradation behaviour, operational lifetime, lifecycle costs, soiling losses, and environmental implications have received little attention. Such considerations are critical in deciding whether the increased expenditure associated with cooling systems is justified during the operating life of a PV plant.

The techno-economic performance of PV system is fundamentally governed by its long-term energy output, operational stability, degradation characteristics, and lifecycle costs. Therefore,

comprehensive assessments that integrate thermal, electrical, economic, and environmental aspects are required to accurately evaluate the feasibility of advanced PV cooling technologies. In particular, the influence of cooling strategies on lifetime energy generation, discounted economic returns, and carbon emission mitigation must be quantified to support investment and design decisions for large-scale PV installation operating in high-temperature environments. The present study builds upon our previous investigations of closed-loop hydronic cooling for PV modules while addressing a distinctly different research question. Earlier studies focused on the development and thermal-electrical performance of the closed-loop cooling concept, including system design parameters, degradation and lifetime behaviour, controlled intermittent-flow operation, and integration with an underground water tank for enhanced heat rejection (Dirawi *et al.* 2026; Dirawi *et al.* 2025; Dirawi *et al.* 2024). In contrast, the present work focuses on the long-term techno-economic implications of deploying the above-ground water tank configuration at utility scale. The analysis extends beyond module-level thermal and electrical performance by scaling the system to a 1 MWp PV plant and integrating degradation-dependent annual and cumulative energy generation with lifecycle economic and environmental assessment over a 25-year project period. This framework enables the additional capital and operating requirements of hydronic cooling to be evaluated against its long-term benefits in energy production, degradation mitigation and service life, thereby addressing practical deployment considerations that were not examined in the previous studies. Accordingly, this study investigates a closed-loop hydronic cooling system for PV panels integrated with an above-ground water tank (PV-AGWT) and compares its performance with that of a common PV system (PV-Com). A 3D numerical model is developed using COMSOL Multiphysics to simulate the thermal and electrical behaviour of both configurations under representative hot and arid climate operating conditions. The annual energy production data employed in techno-economic assessment are derived from the numerical simulations, ensuring consistency between thermal and electrical performance analysis and the economic evaluation framework. Subsequently, a comprehensive assessment is conducted for a 1 MWp PV power plant over a 25-year operational lifetime. The analysis incorporates annual energy production, degradation effects, net present value (NPV), discounted payback period (DPP), levelized cost of electricity (LCOE), and environmental indicators associated with carbon emission reduction.

2. System description of the closed-loop hydronic PV cooling system

The proposed system is a closed-loop hydronic cooling photovoltaic (PV) module consisting of a PV panel, an aluminium absorber plate, copper water tubes, a circulating pump, and a water storage tank, as illustrated in Figure 1. The PV module is composed of a transparent glass cover, monocrystalline silicon solar cells, and an aluminium absorber plate attached to the rear surface of the panel. Copper tubes are installed beneath the absorber plate to circulate cooling water throughout the system. The PV panel has an effective solar collection area of 1.475×0.67 m^2 and contains 36 solar cells with a packing factor of 0.858 and a nominal conversion efficiency of 15%. The 150 Wp PV module was selected to maintain consistency with our previous experimental investigation of the closed-loop hydronic cooling system (Dirawi *et al.* 2025). This also provided established specifications for the associated system components and operating conditions. A 150 L water storage tank and a circulation pump are connected to the module through copper piping, forming a fully closed-loop cooling system. To maximise heat rejection under hot and arid climatic conditions, the water tank and piping are intentionally left uninsulated. This design promotes heat dissipation to the ambient environment, preventing excessive water temperature rise and maintaining the cooling effectiveness of the circulating fluid. During nighttime operation, the enhanced heat loss allows the water to cool naturally, thereby improving the cooling capacity available during subsequent daytime operation.

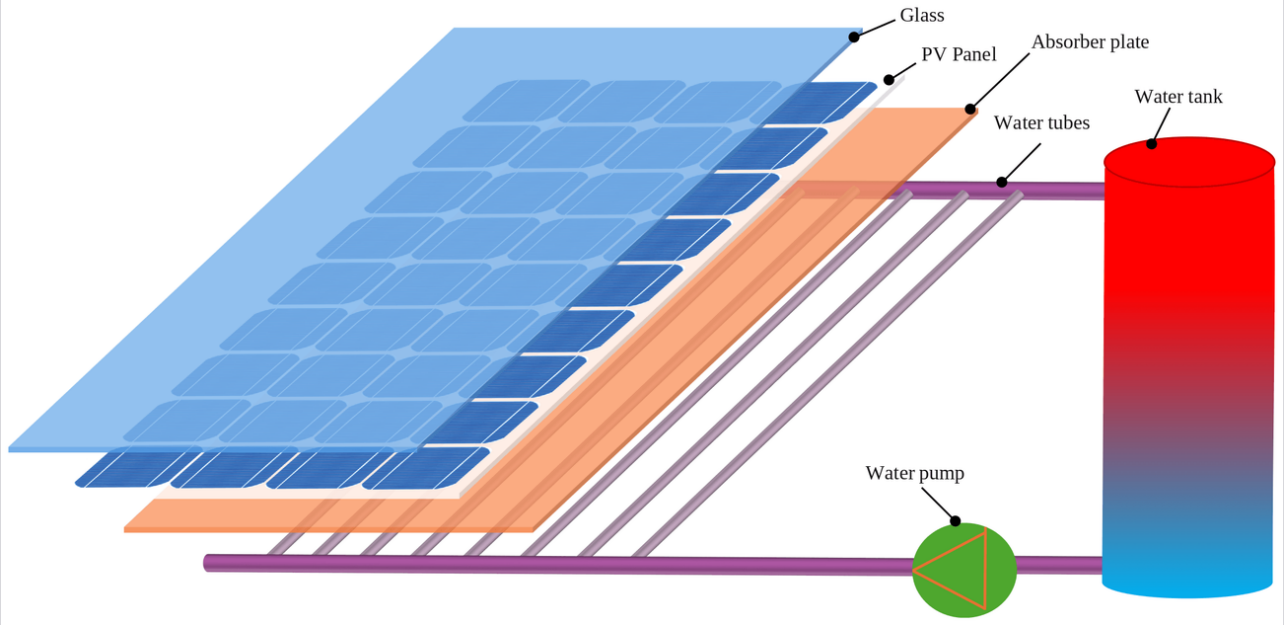

Figure 1. Schematic structure of the closed-loop hydronic cooling of PV panels (Dirawi *et al.* 2025).

The cooling arrangement consists of two manifolds connected to eight parallel copper tubes mounted beneath the absorber plate. The tube configuration ensures adequate thermal contact with the PV module and promotes uniform heat removal across the solar cell rows. The thermophysical, thermal, and optical properties of the glass cover, PV cells, aluminium absorber plate, and copper tubes employed in the numerical model are summarised in Table 1.

Table 1. Thermophysical and optical properties of the PV module components used in the simulation.

Property	Unit	Glass	PV panel (Kumar *et al.* 2020)	Aluminium (Rawat and Sherwani 2023)	Copper tubes (small)
Density	kg/m3	3000	600	2702	8933
Specific heat capacity	J/(kg·K)	750	1255	903	385
Thermal conductivity	W/(m·K)	1.05	0.1	211	401
Thickness	mm	3	1	5	0.7(di=0.0136)
Transmissivity	-	0.9	-	-	-
Absorptivity	-	0.038	0.925	-	-
Emissivity	-	0.88	0.95	-	-

3. Methodology for performance modelling and economic evaluation

3.1. Governing equation

A three-dimensional transient numerical model was developed in COMSOL Multiphysics to simulate the thermal and electrical behaviour of PV system integrated with a closed-loop hydronic cooling loop and an above-ground water tank. The model accounts for heat transfer and fluid flow processes within the PV module and cooling circuit, enabling the prediction of PV temperature and electrical performance under varying operating conditions. The governing equations comprise the conservation of mass, momentum, and energy, which are expressed in Eqs. (1) to (3), respectively. These equations were solved simultaneously using the finite element method (FEM) to obtain the

temperature and flow fields throughout the system and are expressed as follows (COMSOL Multiphysics 2018):

$$\frac{\partial \rho}{\partial t} = \nabla \cdot (\rho u) \tag{1}$$

$$\rho \frac{\partial u}{\partial t} + \rho u \cdot \nabla (u) = -\nabla p + \nabla \cdot \tau - \rho \beta (T - T_{ref})\, g \tag{2}$$

where ρ is the fluid density (kg·m^{-3}), t is time (s), u is the fluid velocity (m·s^{-1}), and p is the fluid pressure (Pa). The parameters μ, β, T, T_{ref}, and g denote the dynamic viscosity (Pa·s), thermal expansion coefficient (K^{-1}), fluid temperature (K), reference temperature (K), and gravitational acceleration (m·s^{-2}), respectively. The continuity equation is given by Eq. (1), while the momentum equation, which includes the buoyancy effect caused by temperature variations, is represented by Eq. (2). Fluid flow within the cooling loop was assumed to be incompressible and laminar.

The energy conservation equation, shown in Eq. (3), was applied to the PV module layers and cooling components to determine heat transfer and temperature distributions.

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T = \nabla \cdot (k \nabla T) + \dot{Q}_v \tag{3}$$

where C_p is the specific heat capacity (J·kg^{-1}·K^{-1}), k is the thermal conductivity (W·m^{-1}·K^{-1}), and Q_v is the volumetric heat generation rate (W·m^{-3}). Internal heat generation within the glass cover and PV cells was evaluated using Eqs. (4) and (5) (Zhou *et al.* 2015), respectively, as expressed below:

$$\dot{Q}_{v,g} = \frac{\alpha_g G}{\delta_g} \tag{4}$$

$$\dot{Q}_{v,PV} = \frac{(\tau\alpha)_{PV} G - \xi P_{elec}}{\delta_{PV}} \tag{5}$$

where $\dot{Q}_{v,g}$ and $\dot{Q}_{v,PV}$ are the volumetric heat generation rates in the glass layer and PV cells (W·m^{-3}), respectively. The parameters α_g, G, δ_g, $(\tau\alpha)_{PV}$, ξ, and δ_{PV} denote the glass absorptivity, solar irradiance (W·m^{-2}), glass thickness (m), effective transmittance–absorptivity product, PV cell packing factor, and PV cell thickness (m), respectively. P_{elec} is the electrical power generated by the PV module (W·m^{-2}). The electrical power output of the PV module was then calculated using Eq. (6) (Zhou *et al.* 2020), while the effective transmissivity-absorptivity relationship was determined according to Eq. (7), as provided below (Duffie and Beckman 2013):

$$P_{elec} = G \tau_g \eta_{ref} \left[1 - \beta_{ref} (T_{PV} - T_{ref})\right] \tag{6}$$

$$(\tau\alpha)_{PV} = \frac{\tau_g \alpha_{PV}}{1 - (1 - \alpha_{PV})\, r_g} \tag{7}$$

where τ_g is the glass transmittance, η_{ref} is the reference PV efficiency, and β_{ref} is the PV temperature coefficient (K^{-1}). The parameters T_{PV}, α_{PV}, and r_g denote the PV cell temperature (K), PV cell absorptivity, and glass reflectivity, respectively. Based on the specifications of a similar system

operating at the same water mass flow rate (Dirawi *et al.* 2025), a pump power requirement of 0.5 W/m^2 was adopted. Consequently, the net power output (P_{net}) of the PV systems is expressed as:

$$P_{net} = P_{elec} - P_{pump} \tag{8}$$

where P_{pump} is the power consumed by the circulation pump. Inverter and other balance-of-system electrical conversion losses were not explicitly considered in the present analysis, as identical electrical conversion components were assumed for both PV configurations. The predicted annual PV energy generation and net power output were subsequently utilised for the economic and environmental assessments presented in this study.

3.2. Numerical procedure and boundary conditions

The three-dimensional transient numerical model was developed in COMSOL Multiphysics and solved using the finite element method. The computational geometry was constructed according to the PV-AGWT configuration and component dimensions described in Section 2 and Table 1. The numerical procedure follows the closed-loop hydronic PV modelling framework developed in our previous studies (Dirawi *et al.* 2025). The coupled heat-transfer and fluid-flow equations were solved simultaneously under transient conditions, with the water flow in the cooling circuit assumed to be incompressible and laminar. A time step of 10 min and a water mass-flow rate of 0.027 kg·s^{-1} were adopted throughout the numerical simulation. Mesh independence of the numerical framework was established in the preceding model-development studies by progressively refining the computational mesh and evaluating the resulting thermal predictions. The mesh-independent configuration was subsequently adopted as the basis for the present numerical analysis. Further details of the mesh-refinement procedure and numerical convergence assessment are provided in (Dirawi *et al.* 2025; Dirawi *et al.* 2024).

The thermal boundary conditions account for convective and radiative heat exchange between the exposed surfaces of the PV system and the ambient environment. Convective heat transfer was considered for the exposed PV module, aluminium absorber, copper tubes and above-ground water tank, while the exterior convective heat-transfer coefficient was determined according to the ambient wind conditions. The edges of the PV module were treated as adiabatic. Within the closed-loop cooling circuit, heated water leaving the PV cooling manifold was directed to the above-ground storage tank and subsequently returned to the PV inlet. The 150 L water tank and connecting pipes were considered uninsulated, allowing heat exchange with the ambient environment. The circulation-pump electricity consumption was accounted for when determining the net electrical output of the PV-AGWT system. Based on the specifications of the previously investigated closed-loop system operating at the same water mass-flow rate (Dirawi *et al.* 2025), a specific pump-power requirement of 0.5 W·m^{-2} was adopted, as expressed in Eq. (8). Detailed hydraulic pressure losses in the external connecting circuit were not independently resolved; instead, circulation was represented through the prescribed water mass-flow rate and the corresponding pump-power requirement. This assumption was applied consistently throughout the comparative analysis.

The numerical framework was previously subjected to mesh-independence assessment and experimental validation (Dirawi *et al.* 2025; Dirawi *et al.* 2024). The good agreement between the numerical and experimental results supports the application of the established modelling framework in the present comparative analysis. The complete experimental setup, mesh-independence assessment and validation procedures are available in the cited studies and are therefore not repeated here.

3.3. Economic and environmental assessment indicators of PV systems

3.3.1. Degradation in power output

The degradation of solar energy systems under actual working conditions could be evaluated through comparison of their real power output (E_t) to an initial or reference power value (E_0) over a long period of outdoor exposure. The annual energy produced by the PV system accounts for the impact of module degradation, as represented in the equation below. PV degradation refers to the progressive reduction in energy generation throughout the operational lifetime of a module. This reduction is primarily attributed to the long-term influence of environmental and operating conditions, which gradually decrease the initial performance of the PV system. The annual power output of the PV module can be estimated as below (Kaaya *et al.* 2019):

$$E_t = E_0\left\{1 - \exp\left(-\left(\frac{\Gamma}{K_T t}\right)\right)^{\phi}\right\} \tag{9}$$

where E_t is the annual energy production in year t, E_0 is the initial annual power output, and K_T is the total degradation rate. The parameters $\emptyset$ and Γ denote the shape factor and power susceptibility, respectively, with Γ is considered an inherent material property.

3.3.2. Initial investment and annual recurring costs

The total initial (C_{int}) cost of each PV system comprises the cost of the photovoltaic modules and all associated components required for installation and operation. For the PV-AGWT configuration, additional costs related to the closed-loop cooling system, including the water storage tank and associated equipment, are also considered. The capital expenditure includes PV modules, inverters, mounting structures, electrical wiring, and installation costs. Annual recurring costs consist of operation and maintenance ($O\&M$) expenses incurred throughout the system lifetime. The estimated initial investment and annual maintenance costs for PV-Com and PV-AGWT systems are summarised in Table 2.

Table 2. Capital investment and annual operation and maintenance costs of the PV systems considered for a 1 MWp installation.

Parameter		System	
	Unit price	PV-Com (US$)	PV-AGWT (US$)
PV modules (150W x 6667)	45 US$/panel (Alomar *et al.* 2023)	300,015	300,015
Inverters	0.06 US$/W (Al Miaari and Ali 2023)	60,003	60,003
Mounting structure, wiring and electrical accessories	36 US$/panel (Al Miaari and Ali 2023)	240,012	240,012
Closed-loop system	-	-	103,339 (Herrando and Markides 2016)
Water storage tank	-	-	109,152 (Herrando and Markides 2016)

Table 2. (continued)

Parameter		System	
Installation cost		155,341 (Al Miaari and Ali 2023)	171,303 (Herrando and Markides 2016; Zondag *et al.* 2006; Zondag *et al.* 2005)
Total initial cost (Cint)		755,371	983,396
Annual O&M cost	1% of initial cost (Kalogirou and Tripanagnostopoulos 2006; Short *et al.* 1995)	7,553	9,833

The cooling-system and storage-tank cost data are adopted from the available literature and are used as comparative cost assumptions in the present analysis; actual utility-scale costs may vary with system design, supplier, installation scale, and regional market conditions.

3.3.3. Net present value and the payback period

The net present value (NPV) represents the difference between the present value of all cash inflows and cash outflows over the project lifetime. It is widely used to assess the economic viability of energy systems by accounting for the time value of money through the application of a discount rate. A positive NPV indicates that the project is economically feasible. In this study, the NPV was calculated as follows (Bhattacharyya 2019):

$$NPV = -C_{int} + \sum_{t=1}^{N} \frac{R_t - C_{O\&M} - C_{grid}}{(1+i)^t} \tag{10}$$

The annual revenue (R_t) was estimated from the electricity generated by PV system and the applicable feed-in tariff (FIT), according to (R_t=E_t·FIT) (Audenaert *et al.* 2010), where (E_t) represents the annual electricity generation. C_{int} and $C_{O\&M}$ denote the initial investment cost and annual operation and maintenance cost, respectively. C_{grid} is the cost of supplementary electricity purchased from the grid that occurs when generation is less than 80% of PV-Com system capacity, (N) is the project lifetime, and (i) is the discount rate, which is set to 5.5% ("Iraq Interest Rate," n.d.). Accordingly, revenues generated from PV electricity production constitute the cash inflows, whereas capital, operation and maintenance, and grid electricity costs are treated as cash outflows.

The discounted payback period (DPP) represents the time required to recover the initial investment while accounting for the time value of money. It corresponds to the year at which the cumulative discounted cash flows become equal to the initial capital cost (Yazdani and Yaghoubi 2021). The DPP is determined as expressed below (Audenaert *et al.* 2010; Yazdani and Yaghoubi 2021):

$$C_{int} = \sum_{t=1}^{DPP} \frac{R_t - C_{O\&M} - C_{grid}}{(1+i)^t} \tag{11}$$

3.3.4. Levelized cost of energy

The levelized cost of energy (LCOE) represents the average cost of generating one kilowatt-hour of electricity over the entire operational lifetime of a PV system. In this study, the LCOE is determined as follows (Obalanlege *et al.* 2022; Yazdani and Yaghoubi 2021):

$$LCOE = \frac{C_{int} + \sum_{t=1}^{N} \frac{C_{O\&M} + C_{grid}}{(1+i)^t}}{\sum_{t=1}^{N} \frac{E_t}{(1+i)^t}} \quad (12)$$

4. Results and discussions

This section presents a comprehensive thermo-economic evaluation of a closed-loop hydronic PV cooling system integrated with an above-ground water tank (PV-AGWT) based on numerical simulations performed using COMSOL Multiphysics. A three-dimensional transient simulation model was developed to investigate the thermal and electrical performance of the PV-AGWT system under continuous 24-hour operating conditions. The analysis considers both the thermal behaviour and energy production of the PV-AGWT system over an extended operating period. In addition, the techno-economic performance of two PV system configurations, namely a common PV system (PV-Com) and the proposed system, is evaluated and compared over a 25-year project evaluation period. Economic feasibility is assessed using cumulative lifecycle costs and the levelized cost of electricity (LCOE), with comparisons made against conventional electricity generation technology. The objective is to determine the most economically viable PV configuration and assess its suitability for deployment under the climatic conditions of Basra, Iraq. Climatic inputs were obtained from the Typical Meteorological Year (TMY) database for Basra, Iraq (30.5° N, 47.8° E), using the climate sources defined in ("Climate.OneBuilding.Org/Weather Data Available online," n.d.; "EnergyPlus Weather Data Available online: energyplus.net/weather," n.d.).

4.1. Annual performance analysis of a single PV panel of 0.988 m² area

This section analyses the annual thermal, electrical performance and degradation rates of two PV system configurations, namely a common PV system (PV-Com) and a closed-loop hydronic PV cooling system integrated with an above-ground water tank (PV-AGWT), under the climatic conditions of Basra. The analysis focuses on the influence of PV-AGWT cooling system on PV operating temperature and electricity generation throughout the year.

4.1.1. Annual power performance of the PV-AGWT system

The analysis employs representative typical-day weather conditions for each month in Basra (Duffie and Beckman 2013), providing an efficient means of evaluating annual system performance while reducing computational requirements. Figure 2 and Figure 3 compare the PV temperature and monthly net power production of the PV-AGWT and PV-Com systems, respectively. The PV-AGWT system employs a closed-loop hydronic cooling circuit connected to an above-ground water tank, which continuously removes excess heat from the rear surface of PV module and thereby improves thermal regulation. As illustrated in Figure 2, PV-AGWT system consistently operates at lower temperatures than PV-Com system throughout the year. The cooling effect becomes more pronounced during periods of high solar irradiation and elevated ambient temperatures, particularly between May and September. During these months, the maximum PV temperature of the PV-AGWT system is reduced by up to about 10°C compared with PV-Com. This reduction is achieved through continuous heat removal by the closed-loop hydronic cooling circuit connected to the above-ground water tank, which efficiently suppresses thermal accumulation within PV module during daytime operation. Consequently, PV-AGWT system exhibits enhanced power generation performance compared with PV-Com throughout the year, as shown in Figure 3. This improvement is attributed to

the lower operating temperatures achieved by the hydronic cooling system. The PV-AGWT design increases the monthly total net power output by about 2.07% compared with PV-Com.

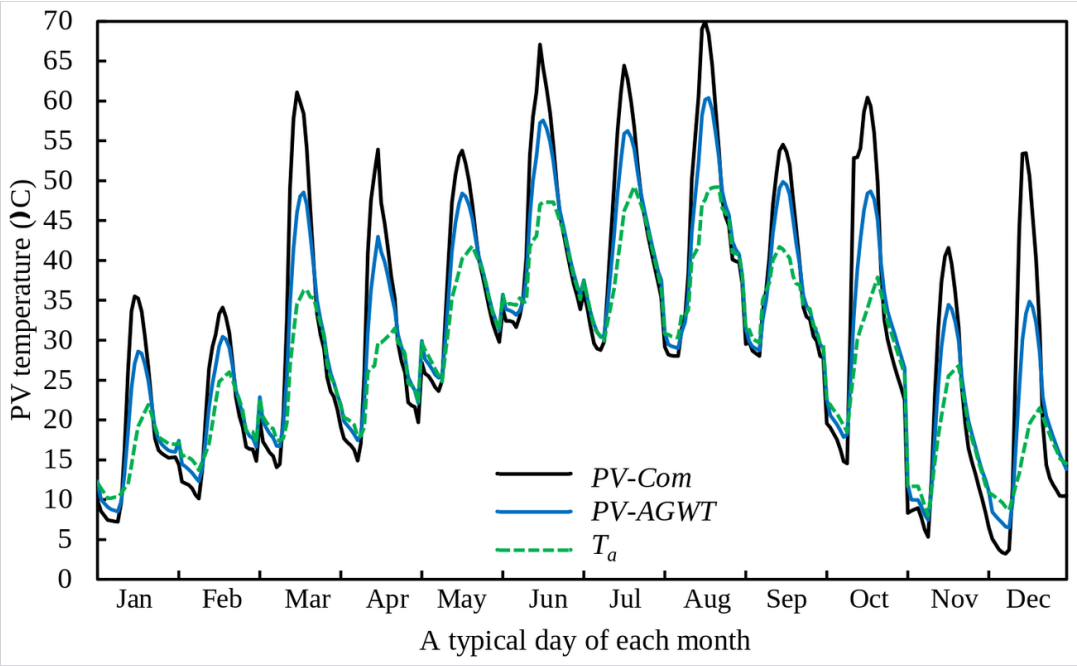

Figure 2. Comparison of PV temperatures for the PV-AGWT and PV-Com systems during a typical day of each month.

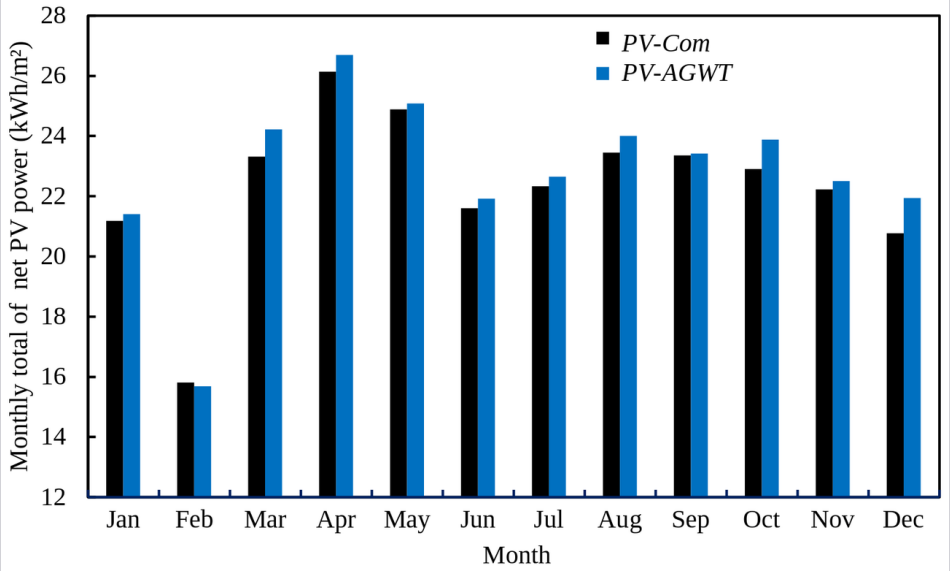

Figure 3. Comparison of monthly total net PV power production for the PV-AGWT and PV-Com systems.

4.1.2. Long-term power degradation and operational lifetime assessment

The long-term degradation of annual power output was evaluated using the degradation model proposed by Kaaya et al. (2021) and the lifetime formulations reported in (Dirawi *et al.* 2025; Dirawi *et al.* 2024). The climatic and operating parameters used in the analysis, together with the corresponding degradation rates, are presented in Table 3.

Table 3. Annual climatic and operating parameters employed in the degradation analysis of PV systems with the estimated degradation rates.

PV systems	T_{mod} (°C)	T_{max} (°C)	T_{min} (°C)	RH (%)	UV dose (kWh·year^{-1}·m^{-2})	Degradation rate (%·year^{-1})
PV-Com	31.98	68.3	3.75	61.5	96.7	1.458
PV-AGWT	30.60	58.9	7.1	61.5	96.7	1.001

Figure 4 compares the degradation of annual power output for the PV-Com and PV-AGWT systems over their operating lifetime. The 80% performance threshold is defined as the time required for the annual power output to decrease to 80% of its initial value (0.8 E_0), which is a widely accepted criterion for PV lifetime assessment (Kaaya *et al.* 2019). The PV-Com system exhibits a degradation rate of 1.458% year^{-1}, reaching the 80% performance threshold after approximately 16.5 years. In contrast, the PV-AGWT system achieves a significantly lower degradation rate of 1.001% year^{-1} owing to its enhanced thermal management. Consequently, the PV-AGWT system maintains higher annual power output throughout the evaluation period and reaches the 80% E_0 threshold after 24.03 years, representing an approximately 45.6% increase in the time to reach the 80% performance threshold compared with PV-Com. These predicted values are comparable in magnitude with degradation and lifetime ranges reported for PV modules operating under other harsh desert conditions. A ten-year field study in the Atacama Desert reported a mean degradation rate of approximately 1.32% year^{-1} and a corresponding projected lifetime of approximately 15.15 years to the 80% performance threshold (Osorio *et al.* 2026).

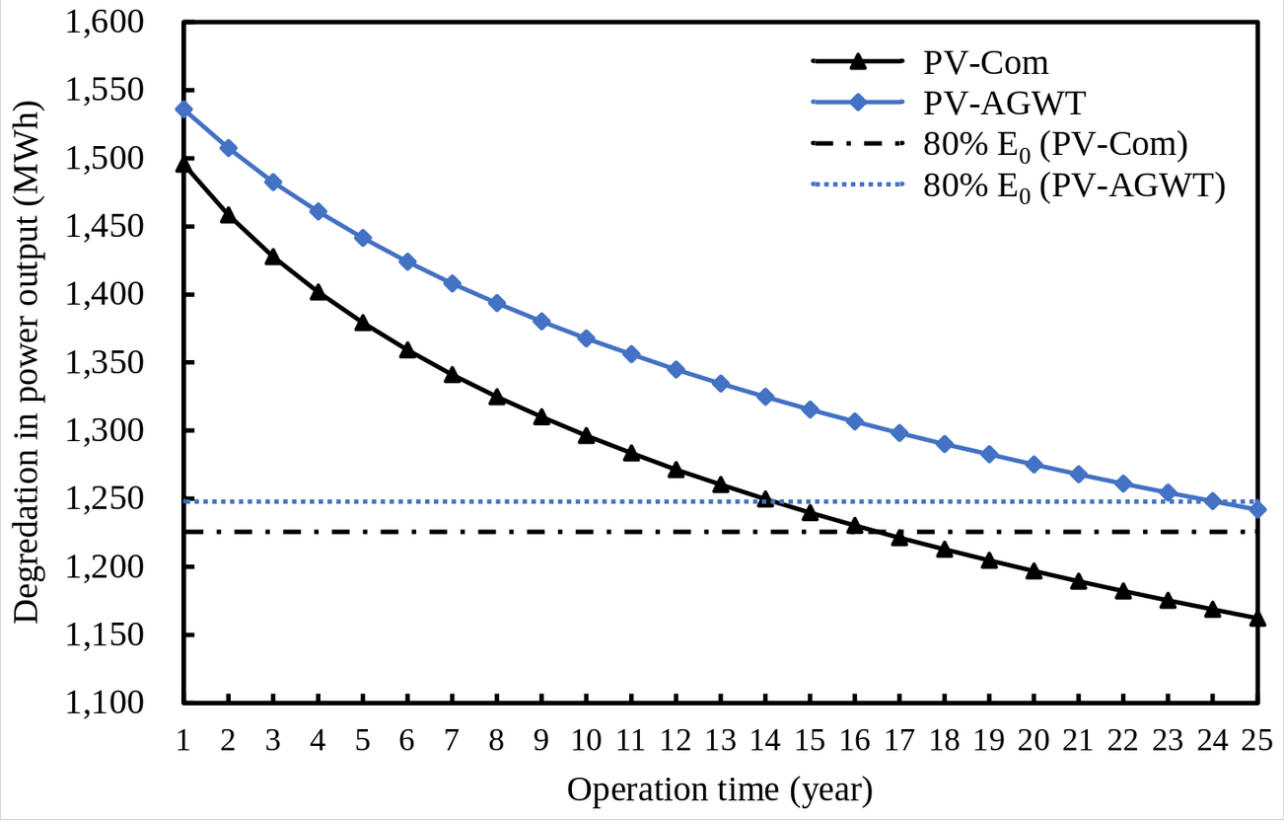

Figure 4. Predicted degradation of annual power output for the PV-Com and PV-AGWT systems as a function of operating time, illustrating the operational lifetime based on the 80% of initial annual energy output (E0).

4.2. Annual energy performance assessment of a 1 MWp PV plant

4.2.1. Power generation performance

A 1 MWp PV power plant was simulated using 150 Wp PV modules, corresponding to a total of 6667 panels. The analysis evaluated annual net power production and cumulative power generation over the 25-year project evaluation period while accounting for module degradation. Furthermore, the minimum power demand threshold was defined as 80% of the initial annual power generation of the PV-Com system. Any power shortage below this threshold during the project evaluation period is assumed to be supplied by the electrical grid to ensure continuous satisfaction of electricity demand.

The PV-Com system generates an annual net power production of 1532.25 MWh. In contrast, the PV-AGWT system achieves an annual net power production of 1559.78 MWh, representing an increase of 27.53 MWh/year or approximately 1.80% relative to PV-Com. This improvement is attributed to the enhanced thermal regulation provided by the closed-loop hydronic cooling system, which reduces operating temperatures and mitigates temperature-related efficiency losses. Figure 5 illustrates the cumulative power generation of the 1 MWp PV plant over the 25-year project evaluation period, including the effect of module degradation. The cumulative energy output reaches 32.04 GWh for PV-Com and 33.80 GWh for PV-AGWT. Consequently, the PV-AGWT system generates an additional 1.76 GWh of electricity over the project lifetime, corresponding to a 5.5% increase compared with PV-Com. These results demonstrate that even modest annual improvements in PV performance can accumulate into substantial lifetime power gains for utility-scale installations. The higher annual and cumulative power production achieved by the PV-AGWT system provides a strong foundation for improving the economic performance and long-term sustainability of PV projects operating in hot and arid regions.

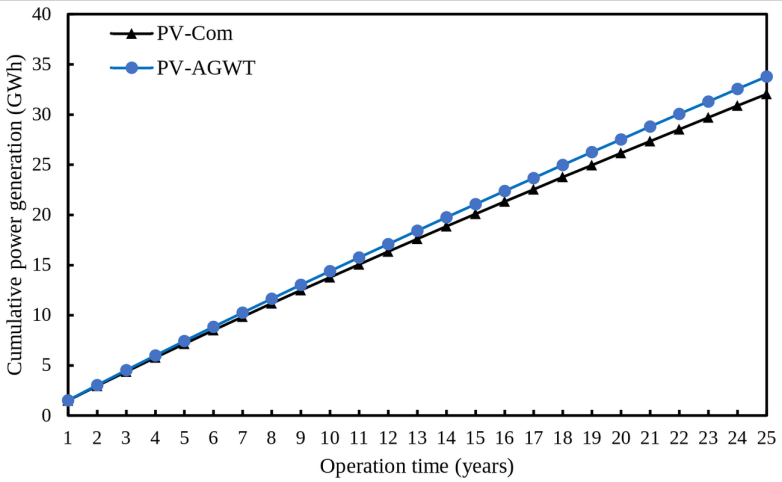

Figure 5. Cumulative power generation of the PV-Com and PV-AGWT systems for a 1 MWp PV power plant, considering module degradation over the 25-year project evaluation period.

4.3. Economic assessment of a 1 MWp PV power plant

4.3.1. Net present values and the payback periods

The economic performance of the PV-Com and PV-AGWT systems was evaluated using the discounted payback period (DPP) and net present value (NPV) over a 25-year project evaluation period. Figure 6 shows the growth of cumulative NPV, accounting for capital investment, operation and maintenance costs, electricity savings, discounting, and inflation. Both systems exhibit negative NPV values during the initial years owing to upfront investment costs. As operating savings accumulate, the NPV increases progressively and becomes positive after the payback period. By the end of the project lifetime, the PV-Com and PV-AGWT systems achieve cumulative NPVs of US$1,778,625 and

US$1,668,914, respectively. Although the additional components required for the AGWT cooling system increase the initial investment cost, the resulting enhancement in electricity generation partially compensates for this economic penalty.

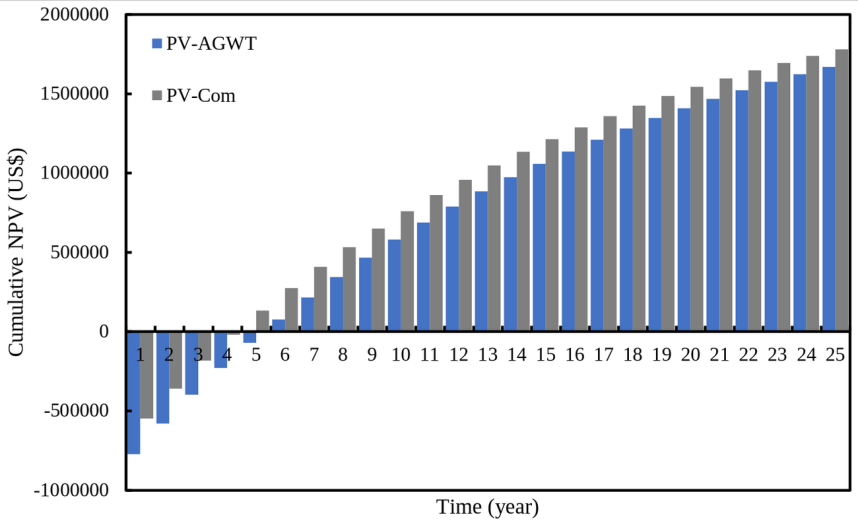

Figure 6. Cumulative net present value (NPV) of the PV-Com and PV-AGWT systems over the 25-year project evaluation period.

The DPP of the PV-Com system is 4.14 years, whereas the PV-AGWT system requires 5.49 years to recover its investment. Despite the longer payback period, the PV-AGWT system achieves full cost recovery within the early stage of the project lifetime and subsequently generates sustained positive cash flows. The difference in DPP between the two configurations is relatively small when compared with the substantial improvement in operational lifetime and cumulative energy production achieved by the PV-AGWT system. Overall, the results indicate that both configurations are financially feasible under the considered conditions. While PV-Com provides the highest NPV, the PV-AGWT system offers a balanced compromise between economic return and technical performance through enhanced energy generation, reduced degradation, and extended service life.

4.3.2. Levelized cost of energy

The levelized cost of energy (LCOE) was evaluated over the 25-year project evaluation period to assess the lifetime cost of electricity generation from the PV systems. The LCOE accounts for all discounted capital, operation, maintenance, and grid electricity costs relative to the total discounted electricity generated throughout the project lifetime. Figure 7 shows the LCOE values of the PV-Com and PV-AGWT systems. The PV-Com configuration achieves the lowest LCOE at approximately 0.05 US$/kWh, reflecting its lower initial investment and operating costs. The PV-AGWT system exhibits a slightly higher LCOE of approximately 0.06 US$/kWh due to the additional cost associated with the hydronic cooling circuit, circulation pump, and above-ground water tank. Despite the higher investment cost, the increase in LCOE remains modest because the PV-AGWT system benefits from enhanced electricity generation and reduced degradation throughout its operational lifetime. Consequently, the additional expenditure is partially offset by the higher cumulative energy production achieved by the cooling system. Overall, both configurations demonstrate competitive electricity generation costs. Although PV-Com remains the most cost-effective option based solely on LCOE, the PV-AGWT system provides additional technical benefits, including improved thermal regulation, higher lifetime energy generation, and extended operational lifetime, making it an attractive alternative for deployment in hot and arid climatic regions.

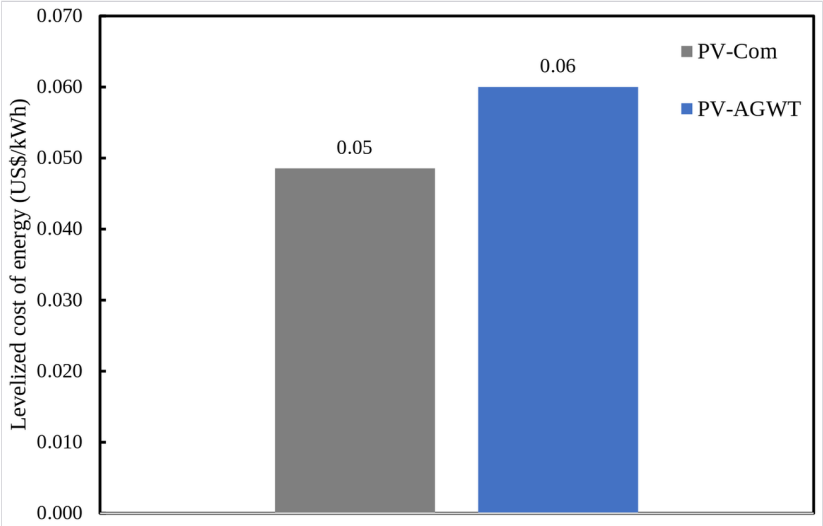

Figure 7. Levelized cost of energy of the PV-Com and PV-AGWT systems over the 25-year project evaluation period.

5. Conclusion

This study employed a three-dimensional transient COMSOL Multiphysics model to investigate the thermo-economic performance of a common PV system (PV-Com) and a closed-loop hydronic PV cooling system integrated with an above-ground water tank (PV-AGWT) under the climatic conditions of Basra, Iraq. The analysis considered thermal performance, energy generation, degradation behaviour, environmental benefits, and economic viability for a 1 MWp PV power plant over a 25-year project evaluation period. Unlike our previous investigations focusing primarily on the thermal, electrical and operational characteristics of hydronic PV cooling, the present study extends the assessment to long-term degradation, lifetime energy production, and economic performance at the 1 MWp scale. The main findings are summarised as follows:

The PV-AGWT system effectively suppresses PV operating temperatures throughout the year, resulting in an average increase of approximately 2.07% in monthly net energy output compared with PV-Com. The improved thermal management also reduces the annual degradation rate from 1.458% year^{-1} to 1.001% year^{-1}, extending the estimated operational lifetime from approximately 16.5 years to 24.03 years, corresponding to a lifetime extension of about 45.6%.For a 1 MWp PV power plant, the PV-AGWT system achieves an annual net energy production of 1559.78 MWh, representing an increase of 27.53 MWh year^{-1} (1.80%) relative to PV-Com. Over the 25-year project evaluation period, cumulative electricity generation reaches 33.80 GWh for PV-AGWT compared with 32.04 GWh for PV-Com, demonstrating that the benefits of thermal regulation accumulate over long-term operation.Both PV configurations demonstrate favourable economic performance. The PV-Com and PV-AGWT systems achieve NPVs of US$1.78 million and US$1.67 million, respectively, with corresponding DPPs of 4.14 and 5.49 years. Although PV-AGWT requires a higher initial investment, the additional cost is partially compensated by increased electricity generation and extended service life. Thus, the higher investment required for PV-AGWT is only partially offset by the additional electricity generation and extended operational lifetime.The PV-AGWT system achieves an LCOE of approximately 0.06 US$/kWh, compared with 0.05 US$/kWh for PV-Com, indicating that the technical benefits of the cooling system are obtained with only a modest increase in electricity generation cost.Overall, the results demonstrate that the PV-AGWT system provides enhanced energy generation, reduced degradation, and extended operational lifetime, although these technical benefits are accompanied by additional capital and O&M requirements. The substantial increase in service life, together with the associated gains in lifetime energy production and environmental benefits, highlights the potential of the PV-AGWT system as a practical cooling strategy for large-scale PV deployment in hot and arid regions.

Nomenclature

Symbol	Description
A	Area (m^2)
C_p	Specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)
DPP	Discounted payback period (year)
E_0	Initial produced energy ($kWh \cdot year^{-1}$)
E_t	Produced energy for the year t ($kWh \cdot year^{-1}$)
FIT	Feed-in tariff ($US\$ \cdot kWh^{-1}$)
g	Acceleration of gravity ($m \cdot s^{-2}$)
G	Solar irradiance ($W \cdot m^{-2}$)
h	Heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
i	Discount rate (%)
k	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
K_T	Degradation rate ($\% \cdot year^{-1}$)
LCOE	Levelized cost of electricity ($US\$ \cdot kWh^{-1}$)
NPV	Net present value (US$)
p	Fluid pressure (Pa)
P	Carbon dioxide amount for each kWh of electricity ($kg \cdot kWh^{-1}$)
P_{elec}	Electrical power ($W \cdot m^{-2}$)
P_{net}	Net electrical power ($W \cdot m^{-2}$)
P_{pump}	Pump power consumption ($W \cdot m^{-2}$)
Q_v	Volumetric heat generation rate ($W \cdot m^{-3}$)
r_g	Glass reflectivity (-)
RH	Relative humidity (%)
t	Time (s)
T	Temperature (°C or K)
u	Fluid velocity ($m \cdot s^{-1}$)

Greek symbols

Symbol	Description
τ	Transmissivity
τα	Effective transmissivity-absorptivity
α	Absorptivity
δ	Layer thickness (m)
β	Thermal expansion coefficient (K^{-1})
ε	Emissivity
σ	Stefan-Boltzmann constant (5.67×10^{-8} $Wm^{-2}K^{-4}$)
ρ	Density ($kg \cdot m^{-3}$)
ξ	Packing factor
η	Efficiency (%)
Γ	Power susceptibility
μ	Dynamic viscosity ($kg \cdot m^{-1} \cdot s^{-1}$)
Ø	Shape factor

Abbreviations

Abbreviation	Description
O&M	Operation and maintenance
PV	Photovoltaic
PV-AGWT	Photovoltaic-above-ground water tank
PV-Com	Common PV system

Subscript

Subscript	Meaning
a	Ambient
av	Average
g	Glass
max	Maximum
min	Minimum
O&M	Operation and maintenance
PV	Photovoltaic
ref	Reference
t	Time

Declarations

Author contributions. Hazim Dirawi: Conceptualisation; Data curation; Formal analysis; Investigation; Methodology; Project administration; Software; Validation; Visualisation; Writing - Original Draft; Writing - Review & Editing. Qiliang Wang: Formal analysis; Funding acquisition; Supervision; Validation; Writing - Original Draft; Writing - Review & Editing. Yuehong Su: Conceptualisation; Funding acquisition; Resources; Supervision; Validation; Writing - Original Draft; Writing - Review & Editing.

Conflicts of interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability. The data that support the findings of this study are available from the corresponding author upon reasonable request.

Ethics. Ethical approval was not required for this study, as it did not involve human participants, animals, personal data, or biological specimens.

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