

Solar-driven cogeneration of electricity and water vapor via photovoltaic-enabled contactless evaporation

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HIGHLIGHTS

- PV-enabled CLE is proposed for cogeneration of electricity and water vapor.
- Coupled 3-D multiphysics model with spectral splitting is developed.
- Ambient conditions and air gap thickness jointly govern system performance.
- c-Si, CdTe and PSC systems exhibit distinct electricity–water–vapor production trade-offs.
- PSC–CLE achieves $\eta_o = 78.8\%$, a 155% relative increase over absorber-only CLE.

ARTICLE INFO

Keywords:

Contactless evaporation
Electricity–water–vapor cogeneration
Multiphysics modeling
Solar energy utilization
Semi-transparent photovoltaic cell
Spectral splitting

ABSTRACT

Solar-driven cogeneration systems integrating photovoltaic (PV) technology with waste-heat-driven interfacial evaporation offer a sustainable route to the simultaneous production of electricity and water vapor. However, salt accumulation in conventional contact-based interfacial evaporators remains a major obstacle to long-term operation. Contactless evaporation (CLE) physically separates the solar absorber from the saline feed, thereby preventing direct brine contact and salt deposition on the absorber surface. Nevertheless, CLE has not yet been explored for PV-enabled electricity–water–vapor cogeneration. Here, we propose a photovoltaic-enabled contactless evaporation (PV–CLE) system in which PV cells positioned above the water surface generate electricity, while their residual heat drives contactless evaporation across an air gap via thermal radiation. The use of semi-transparent PV (STPV) cells further allows transmitted near-infrared solar radiation to directly heat the water while mitigating PV overheating, thereby enabling more effective full-spectrum solar utilization. A coupled three-dimensional multiphysics model incorporating a spectral-splitting framework is developed to elucidate the interacting optical, electrical, thermal, and mass-transport processes within the proposed system. Three representative PV technologies, namely crystalline silicon (c-Si), cadmium telluride (CdTe), and perovskite solar cells (PSCs), are systematically evaluated over a range of ambient temperatures, relative humidities, wind speeds, and air-gap thicknesses and benchmarked against an absorber-only CLE system. The results reveal distinct performance trade-offs: c-Si achieves the highest solar-to-electricity efficiency (19.2%), CdTe delivers the highest solar-to-vapor efficiency (45.8%), and the PSC-based system attains the highest overall equivalent efficiency of 78.8% at an air-gap thickness of 5 mm, representing a 155% increase relative to the absorber-only CLE reference system. Under baseline conditions, the PSC-based system operates at approximately 42.2 °C, which is 14.8 °C lower than the operating temperature of the c-Si system. These findings establish PV–CLE as a promising technology for efficient electricity and water-vapor cogeneration, advancing sustainable solutions at the water–energy nexus.

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<https://doi.org/10.1016/j.apenergy.2026.129147>

Received 15 July 2026; Received in revised form 30 September 2026; Accepted 18 October 2026

Available online 28 October 2026

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Nomenclature*Latin symbols*

$\dot{m}$	Water-vapor production rate, $\text{kg}/(\text{m}^2 \cdot \text{s})$
$\mathbf{g}_w$	Diffusive vapor flux, $\text{kg}/(\text{m}^2 \cdot \text{s})$
$\mathbf{q}$	Conductive heat flux, W/m^2
$\mathbf{q}_r$	Radiative heat flux, W/m^2
$\mathbf{u}$	Velocity vector, m/s
a	Air-gap thickness between the PV component and the water surface, mm
$c_{p,a}$	Specific heat capacity of air at constant pressure, $\text{J}/(\text{kg} \cdot \text{K})$
$c_{p,v}$	Specific heat capacity of water vapor at constant pressure, $\text{J}/(\text{kg} \cdot \text{K})$
c_p	Specific heat capacity of moist air at constant pressure, $\text{J}/(\text{kg} \cdot \text{K})$
C_{sat}	Saturation vapor concentration, mol/m^3
C_v	Water vapor concentration, mol/m^3
D	Diffusion coefficient of water vapor in air, m^2/s
d_{ch}	Water channel diameter, mm
E_b	Blackbody emissive power, W/m^2
F_{ij}	View factor from surface i to surface j
$G_{\text{PV}}(\lambda)$	Spectral solar irradiance incident on the PV cells, $\text{W}/(\text{m}^2 \cdot \text{nm})$
$G_{\text{sun}}(\lambda)$	Spectral solar irradiance incident on the Earth's surface, $\text{W}/(\text{m}^2 \cdot \text{nm})$
$G_w(\lambda)$	Spectral solar irradiance reaching the water surface, $\text{W}/(\text{m}^2 \cdot \text{nm})$
h_{ch}	Water channel depth, mm
h_{fg}	Latent heat of vaporization of water, J/kg
J	Radiosity, W/m^2
l_{ch}	Water channel spacing, mm
L_{PV}	Length of the PV cells, mm
L_{wb}	Underlying water body length, mm
M_v	Molar mass of water vapor, kg/mol
P_{PV}	Electric power density generated by the PV cells, W/m^2
Q	Volumetric heat source term, W/m^3
$Q_{\text{abs,b}}$	Solar energy absorbed within the thin water layer, W/m^2
$Q_{\text{abs,g}}$	Solar energy absorbed by the glass layer, W/m^2
$Q_{\text{abs,ins}}$	Solar energy absorbed by the insulation surface, W/m^2
$Q_{\text{abs,PV}}$	Solar energy absorbed by the PV cells, W/m^2
$Q_{\text{h,PV}}$	Residual heat generated in the PV cells, W/m^2
Q_{H}	Heat source term associated with vapor diffusion, W/m^3
$q_{\text{rad,PV}}$	Net radiative heat flux at the rear PV surface, W/m^2
$q_{\text{rad,w}}$	Net radiative heat flux at the water surface, W/m^2
R	Moisture source term, $\text{kg}/(\text{m}^3 \cdot \text{s})$

R_{PV}	Average reflectance of the PV cells
T_{amb}	Ambient temperature, K or $^{\circ}\text{C}$
T_{PV}	PV operating temperature, K or $^{\circ}\text{C}$
T_{ref}	Reference temperature, K or $^{\circ}\text{C}$
T_{sky}	Equivalent sky temperature, K or $^{\circ}\text{C}$
T_w	Average water surface temperature, K or $^{\circ}\text{C}$
w	Weighting coefficient

Abbreviations

3-D	Three-dimensional
c-Si	Crystalline silicon
CdTe	Cadmium telluride
CLE	Contactless evaporation
EQE	External quantum efficiency
PSC	Perovskite solar cell
PV	Photovoltaic
RE	Relative error
STPV	Semi-transparent photovoltaic

Greek symbols

α_g	Absorptance of the glass layer
α_{ins}	Absorptance of the insulation surface
β	Temperature coefficient of PV electrical efficiency, K^{-1}
δ_{air}	Convection-cover air thickness, mm
δ_g	Glass thickness, mm
δ_{ins}	Insulation-foam thickness, mm
δ_{PV}	PV-layer thickness, mm
δ_{wb}	Underlying water body thickness, mm
δ_{wl}	Thin water layer thickness, mm
$\eta_{\text{el},0}$	Electrical efficiency of the PV cells at the reference temperature, %
η_{el}	Electrical efficiency of the PV cells, %
η_e	Solar-to-electricity efficiency, %
η_o	Overall equivalent efficiency, %
η_v	Solar-to-vapor efficiency, %
λ	Wavelength, nm
μ	Dynamic viscosity, $\text{Pa} \cdot \text{s}$
ϕ_{amb}	Ambient relative humidity
ρ	Density, kg/m^3
σ	Stefan–Boltzmann constant, $\text{W}/(\text{m}^2 \cdot \text{K}^4)$
τ_g	Transmittance of the glass layer
$\tau_{\text{PV}}(\lambda)$	Spectral transmittance of the PV cells
ε	Surface emittance
ε_c	Emittance of the convection cover outer surface
ε_{PV}	Emittance of the rear surface of the PV cells
ε_w	Emittance of the water surface

1. Introduction

Freshwater scarcity and energy insecurity are increasingly interconnected challenges to sustainable development, particularly in remote and resource-constrained regions where access to clean water and reliable electricity remains limited [1]. Although approximately 97.5% of Earth's water is stored in seas and oceans, converting this abundant resource into usable freshwater remains technically and economically demanding [2]. Conventional desalination technologies, such as reverse osmosis [3] and multistage flash distillation [4], are effective at large scales but typically require substantial energy inputs, complex infrastructure, and high operating costs, which limit their suitability for decentralized applications [5]. Solar-driven interfacial evaporation has therefore attracted considerable attention as a potentially low-cost, passive approach to water-vapor production because it localizes heat at the air–water interface and thereby enhances evaporation [6].

Meanwhile, photovoltaic (PV) technology provides a mature and scalable pathway for distributed solar-to-electricity conversion [7]. Integrating PV cells with interfacial evaporation has thus emerged as a promising strategy for decentralized electricity–water-vapor cogeneration [8]. In these integrated systems, saline water is continuously supplied through wicking structures to a wetted evaporation interface that is in direct contact with the solar absorber. This integration enables simultaneous electricity generation and thermally driven evaporation while lowering the PV operating temperature and mitigating the associated performance losses [9,10]. PV-enabled electricity–water-vapor cogeneration systems can be broadly classified according to the optical properties of their PV components. In opaque-PV configurations (Fig. 1(a)), the PV cells function as the solar absorber, and their residual heat is transferred to an adjacent wicking layer to drive evaporation [11]. However, the absorption of below-band-gap radiation imposes an additional thermal load on the PV cells, increasing their operating temperature and reducing their electrical efficiency. Spectral-splitting

photovoltaic–thermal (PV–T) systems address this limitation by using an optical splitter to direct different portions of the solar spectrum to separate photovoltaic and thermal receivers, with the recovered thermal energy available for downstream desalination processes such as membrane distillation [12]. By contrast, semi-transparent PV (STPV) configurations (Fig. 1(b)) use the PV cells as a spectral splitter, transmitting a portion of the below-band-gap solar radiation to an underlying absorber for thermal utilization. Ji et al. [13] demonstrated this concept using semi-transparent polymer solar cells, whereas Chen et al. [14] employed semi-transparent silicon solar cells. This spectral-allocation strategy redistributes incident solar energy between photovoltaic conversion and evaporation, thereby reducing the PV thermal load and enhancing full-spectrum solar utilization.

Despite these advances, existing PV-enabled solar electricity–water vapor cogeneration systems have primarily been developed using contact-based interfacial evaporation architectures. Continuous evaporation concentrates salt at the evaporation interface, where crystallization can obstruct water-transport pathways and degrade evaporation performance, particularly under high-salinity conditions or during prolonged operation [15]. Considerable effort has therefore been devoted to mitigating salt accumulation in contact-based architectures, including enhanced salt back-diffusion induced by Marangoni flow [16], accelerated water replenishment [17], Janus materials [18], and self-cleaning or self-rotating structures [19]. Although these strategies can effectively alleviate salt accumulation, they rely on specialized materials or structural designs to regulate the intrinsically coupled transport of water and salt. This coupling remains a fundamental challenge to the long-term operation of contact-based solar-driven interfacial evaporation systems.

Contactless evaporation (CLE) offers a fundamentally different approach by physically separating the solar absorber from the evaporation interface with an air gap [20]. The absorber converts incident solar radiation into heat and emits long-wave thermal radiation toward the water surface. This radiation is strongly absorbed within a sub-100 μm thick surface layer, thereby directly heating the evaporation interface [21]. Evaporation occurs directly at the saline water–air interface without a wicking layer, thereby decoupling the solar absorber from the liquid-phase transport of water and salt that is inherent in contact-based systems. Cooper et al. [22] first demonstrated a CLE system employing a spectrally selective absorber to generate superheated steam. Menon et al. [23] subsequently developed a photothermal umbrella evaporator for zero-liquid-discharge applications. Building on this contactless principle, Zhang et al. [24] introduced a wick-free, confined-water-layer architecture (Fig. 1(c)) to improve thermal localization while maintaining salt tolerance. Subsequently, Zheng et al. [25] enhanced vapor transport by developing a scalable three-dimensional (3-D) CLE architecture based on this design. Collectively, these studies demonstrate the considerable salt-management potential of wick-free CLE architectures for solar-driven interfacial evaporation. However, existing CLE research has focused primarily on enhancing solar-to-vapor efficiency through heat and mass transfer management, whereas the integration of photovoltaic energy conversion into contactless evaporation architectures remains largely unexplored.

To address this gap, a PV-enabled contactless evaporation (PV–CLE) system is proposed to extend conventional CLE to electricity–vapor cogeneration while preserving its wick-free architecture, as schematically illustrated in Fig. 2. PV cells are suspended above a confined water layer, such that residual PV heat drives evaporation predominantly through radiative transfer across the intervening air gap. Beyond this functional integration, STPV enables spectral energy management by converting part of the incident solar spectrum into electricity while transmitting below-band-gap radiation directly to the underlying water. The transmitted radiation complements residual PV heat in driving evaporation, thereby enabling more effective utilization of the incident solar spectrum. Three representative PV technologies with distinct spectral characteristics are considered: opaque crystalline silicon (c-Si), semi-transparent cadmium telluride (CdTe), and perovskite solar

cells (PSCs). The coupled energy-conversion and transport pathways give rise to nontrivial trade-offs between electrical output and evaporation performance. Accordingly, a 3-D multiphysics model coupled with a spectral-splitting framework is developed to quantify solar-energy allocation and the associated heat and mass transfer processes. The effects of ambient conditions and air-gap thicknesses are systematically investigated, and the influence of salinity is assessed to evaluate system performance under seawater and concentrated-brine conditions. The PV–CLE configurations are benchmarked against a conventional absorber-only CLE system to quantify the energy-utilization benefits of PV integration. The results elucidate how PV technology and spectral energy allocation govern the trade-off between electricity generation and water-vapor production, providing design guidelines for enhancing overall solar-energy utilization in PV–CLE systems.

2. Methodology

This section presents the methodological framework developed to evaluate the proposed PV–CLE cogeneration system. First, the system configuration and selected PV technologies are introduced. Next, a coupled multiphysics modeling framework is developed and numerically solved to elucidate solar energy partitioning and the associated coupling with heat and mass transfer processes within the system. Finally, performance metrics are defined to quantify electricity generation, water-vapor production, and overall solar-energy utilization.

2.1. Configuration of the proposed PV–CLE cogeneration system

Fig. 2 illustrates the configuration of the proposed PV–CLE cogeneration system. A convection cover consisting of a 2-mm-thick glass layer and a 5-mm-thick air layer, is positioned above the PV cells to suppress convective heat loss to the surroundings [24]. The outer surface of the glass is assigned a low thermal emittance in the model to reduce radiative heat loss to the ambient environment [26]. Incident solar radiation first passes through the transparent cover and reaches the PV cells, where a portion of the absorbed solar energy is converted into electricity through the photovoltaic effect. Because of the limited photovoltaic conversion efficiency, a substantial fraction of the absorbed energy is converted into heat, thereby increasing the temperature of the PV cells. The resulting thermal radiation from the back of the cells can be efficiently absorbed by the underlying water layer, increasing its temperature and promoting evaporation. To enhance downward radiative heat transfer and simultaneously improve PV cooling, a high emittance coating is applied to the rear surface of the PV cells [23]. For STPV cells, below-band-gap solar radiation is additionally transmitted through the cells and absorbed directly by the underlying water layer.

Directly beneath the PV cells, a floating thermal-insulation foam layer, perforated with 2.5-mm-diameter channels, is submerged in the water reservoir. A balancing weight stabilizes the foam layer and maintains a confined water layer approximately 5 mm thick. This wick-free CLE configuration and its geometric dimensions follow the architecture originally proposed and validated theoretically and experimentally by Zhang et al. [24] and subsequently adopted by Zheng et al. [25]. The confined water layer is hydraulically connected to the surrounding reservoir through the channels, allowing for continuous water replenishment during evaporation while limiting conductive heat loss to the bulk water. A narrow air gap separates the PV cells from the water surface, enabling contactless radiative heat transfer from the rear surface of the PV cells to the water. The air gap also permits ambient airflow, which facilitates the removal of the generated water vapor.

In the STPV–CLE systems, the overall architecture remains unchanged, except that the STPV cell acts as a spectral splitter: it selectively absorbs above-band-gap photons for photovoltaic conversion while transmitting a fraction of the below-band-gap solar radiation. The transmitted radiation is absorbed by either the confined water layer or the photothermal coating on the upper surface of the floating insulation foam, thereby supplying additional energy for evaporation. Meanwhile,

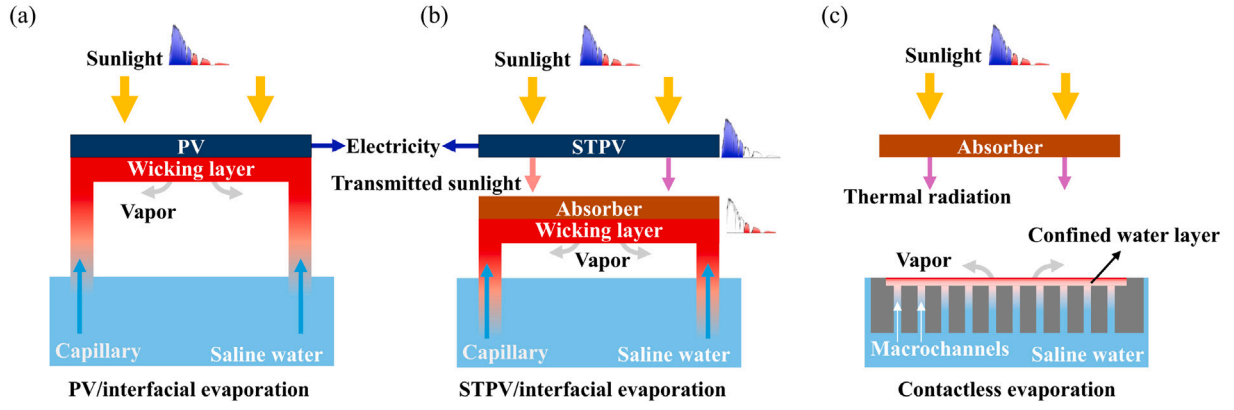


Fig. 1. Schematic comparison of contact-based PV/STPV interfacial evaporation and wick-free, contactless evaporation architectures.

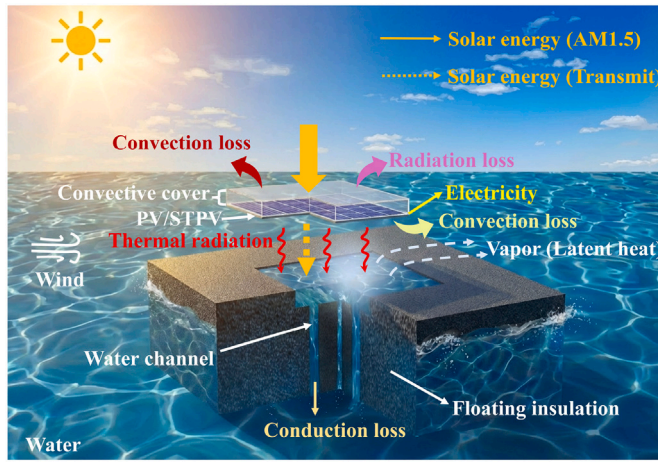


Fig. 2. Schematic of the proposed PV/STPV-CLE system and its principal energy transfer pathways.

residual heat generated within the STPV cell produces thermal-infrared emission from its rear surface, which is absorbed by the underlying water and further contributes to evaporation. Collectively, these pathways enable broader utilization of the incident solar spectrum through photovoltaic electricity generation, direct absorption of transmitted solar radiation, and recovery of residual PV heat within the wick-free CLE architecture.

Fig. 3 presents the spectra of incident solar radiation and blackbody emission at 100 °C, together with the wavelength-dependent penetration depth of radiation in liquid water, calculated from the spectral absorption and scattering coefficients of water [27]. The thermal-infrared radiation emitted by the PV cells (red zone) is absorbed predominantly within a surface water layer less than 100 μm thick, thereby directly driving interfacial evaporation [23]. Thus, the energy available for evaporation beneath an STPV cell originates from two radiative sources: longwave thermal radiation emitted from the rear surface of the cell and below-band-gap solar radiation transmitted through the cell. The contribution of transmitted solar radiation is governed by the wavelength-dependent transmittance of the STPV cells. Solar radiation at wavelengths longer than approximately 1320 nm (light-orange zone) is absorbed directly within the 5-mm-thick water layer. By contrast, shorter-wavelength photons (orange zone), for which water is relatively transparent, penetrate through the confined water layer. To capture this otherwise unabsorbed radiation, a high-absorptance black coating ($\alpha > 0.99$) is applied to the upper surface of the floating insulation foam [28].

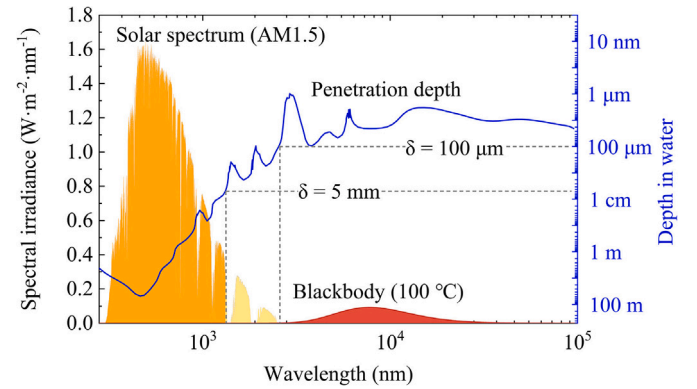


Fig. 3. Spectral distributions of solar irradiance and blackbody emissive power at 100 °C, together with the wavelength-dependent penetration depth of radiation in liquid water.

2.2. Selected PV technologies

In this study, a high-efficiency commercial monocrystalline silicon cell from JinkoSolar Co., Ltd. is considered alongside two STPV technologies: the CdTe cells reported by Li et al. [29] and the PSC reported by Zhang et al. [30]. The external quantum efficiency (EQE) spectrum adopted for the c-Si cell is obtained from Masala et al. [31]. Fig. 4(a) compares the EQE spectra of the three PV technologies. The c-Si cell exhibits a broad spectral response spanning the visible and near-infrared regions up to approximately 1100 nm. By comparison, the CdTe cells exhibit a strong EQE response between approximately 450 and 800 nm, whereas the PSC exhibits a strong response between approximately 400 and 750 nm. In an opaque c-Si cell, a substantial fraction of the incident solar energy that is not converted into electricity is dissipated as heat, resulting in an elevated operating temperature and a corresponding reduction in electrical performance. STPV cells can partially mitigate this thermal penalty by acting as spectral splitters: photons within their photoactive spectral ranges are utilized for photovoltaic conversion, whereas a substantial fraction of the longer-wavelength radiation is transmitted. This spectral selectivity reduces parasitic absorption and heating within the PV cells, thereby alleviating the temperature-induced reduction of electrical performance.

Fig. 4(b) presents the spectral transmittance of the two selected STPV technologies. Both cells exhibit low transmittance in the visible region, followed by a pronounced increase at longer wavelengths. The transmittance of the CdTe cell begins to increase gradually at approximately 550 nm and reaches approximately 0.8–0.9 in the near-infrared region. By contrast, the PSC exhibits a considerably sharper

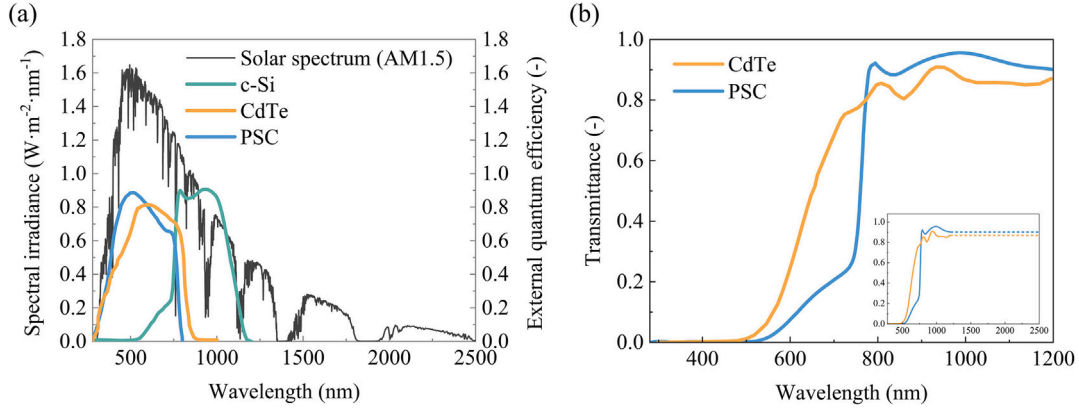


Fig. 4. (a) Spectral solar irradiance and EQEs of the selected PV technologies; (b) Spectral transmittance of the CdTe [29] and PSC [30] cells.

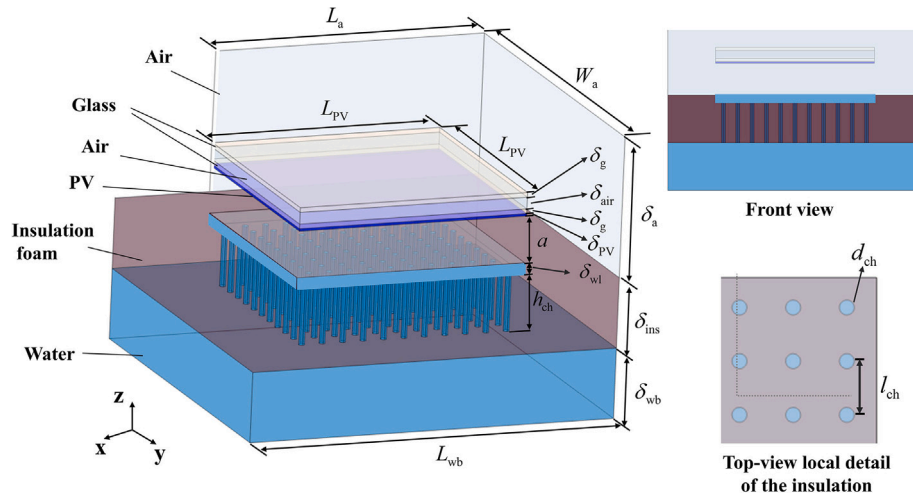


Fig. 5. Geometry of the considered PV-CLE cogeneration system.

transmittance onset near 780 nm, beyond which its transmittance remains above 0.9 throughout most of the near-infrared region. These spectral characteristics demonstrate the wavelength selective transparency of both STPV cells, with the PSC exhibiting a more distinct spectral cutoff and slightly higher near-infrared transmittance. For a consistent performance comparison, all PV technologies are modeled using the same geometry, while their technology specific optical and electrical properties are prescribed accordingly.

2.3. Numerical model for performance evaluation

To quantify the coupled electricity generation and evaporation performance of the PV-CLE system, a steady-state 3-D multiphysics model is developed and numerically solved using COMSOL Multiphysics 6.2. The model accounts for (i) the spectral allocation of incident solar energy; (ii) temperature-dependent photovoltaic electricity generation; and (iii) conductive and convective heat transfer, radiative heat transfer, and vapor transport throughout the integrated system.

The computational domain, shown in Fig. 5, comprises a convection cover, PV cells, a confined water layer connected to the bulk water through an array of channels, a floating insulation foam, the surrounding water reservoir, and the external air domain. The geometric parameters of each component are summarized in Table 1. The air-gap thickness between the PV cell and the water surface is treated as a key geometric parameter. Previous studies have identified 1 mm as the lower limit for

effective heat transfer; however, maintaining such a narrow gap under practical seawater conditions is challenging because of surface waves and fabrication tolerances [25]. By contrast, a 4-mm air gap has been adopted in compact devices with a characteristic width of approximately 3.5 cm, indicating that a moderately larger gap may provide a more practical balance between heat transfer performance and operational robustness under realistic conditions [23]. Accordingly, the range of air-gap thicknesses investigated in this study is selected based on the values reported in the literature and the practical constraints associated with a 10-cm-wide device.

The following assumptions are adopted to simplify the solution procedure while preserving the physical integrity of the model:

- (1) The system operates under steady-state conditions.
- (2) The rear surface of the PV cells and the water surface are treated as diffuse-gray surfaces for thermal radiation exchange.
- (3) The PV cell is represented as a single homogeneous solid layer using the equivalent thermophysical properties reported in Ref. [32]. The supporting and mounting structures of the PV cells are neglected.
- (4) Radiative interactions with the air inside the convection cover and the air gap are neglected because the extinction coefficient of air is substantially lower than that of water and of solid materials [33].

Table 1
Geometric parameters of the considered PV–CLE cogeneration system.

Geometric parameters	Value (mm)
PV cell length (L_{PV})	100
Glass thickness (δ_g)	2
Convection cover air thickness (δ_{air})	5
PV layer thickness (δ_{PV})	1
Air-gap thickness, a	5–20
Thin water layer thickness (δ_{wl})	5
Water channel depth (h_{ch})	25 [24]
Water channel diameter (d_{ch})	2.5 [24]
Water channel spacing (l_{ch})	9 [24]
Insulation foam thickness (δ_{ins})	30
Underlying water body thickness (δ_{wb})	30
Underlying water body length (L_{wb})	160
Air domain length (L_a)	130
Air domain width (W_a)	160
Air domain height (δ_a)	50

2.3.1. Governing equations

A coupled multiphysics model is developed to describe airflow, heat transfer, surface-to-surface radiation, evaporation, and water-vapor transport within the proposed system. The airflow field governs the convective transport of heat and water vapor. Airflow is modeled as incompressible and laminar, with buoyancy effects incorporated using the Boussinesq approximation. The applicability of the laminar flow assumption over the investigated range of steady-state operating conditions is evaluated in Appendix A.1. Accordingly, the air density is assumed to be constant, except in the buoyancy term, while the dynamic viscosity of air and the water-vapor diffusivity are treated as temperature-dependent properties. Surface-to-surface radiation accounts for radiative heat exchange between the water surface and the rear surface of the PV cell, thereby affecting the temperature field. Water vapor transport is coupled with heat transfer through the latent heat associated with evaporation. The governing equations are formulated in Cartesian coordinates as follows.

• Continuity:

$$\rho(\nabla \cdot \mathbf{u}) = 0 \quad (1)$$

where ρ [kg/m³] is the density of the fluid, and $\mathbf{u}$ [m/s] is the velocity vector.

• Momentum conservation:

$$\rho(\mathbf{u} \cdot \nabla)\mathbf{u} = \nabla \cdot [-p\mathbf{I} + \mu(\nabla\mathbf{u} + (\nabla\mathbf{u})^T)] + \mathbf{F} \quad (2)$$

where $\mathbf{F}$ [N m⁻³] is the volume force vector, p [Pa] is the pressure, and μ [Pa · s] is the viscosity of the fluid in the computational domain.

• Energy conservation:

$$\rho c_p(\mathbf{u} \cdot \nabla T) + \nabla \cdot (\mathbf{q} + \mathbf{q}_r) = (\mathbf{u} \cdot \nabla p) + \tau : \nabla\mathbf{u} + Q_H + Q \quad (3)$$

$$Q_H = -(c_{p,v} - c_{p,a})\mathbf{g}_w \cdot \nabla T \quad (4)$$

where c_p [J/(kg · K)] is the specific heat capacity of moist air at constant pressure, T [K] is the absolute temperature, $\mathbf{q}$ [W/m²] is the heat flux due to conduction, $\mathbf{q}_r$ [W/m²] is the heat flux due to radiation, τ [Pa] is the viscous stress tensor, Q [W/m³] contains heat sources other than viscous dissipation, $c_{p,v}$ [J/(kg · K)] is the specific heat capacity at constant pressure of water vapor, $c_{p,a}$ [J/(kg · K)] is the specific heat capacity at constant pressure of air, and $\mathbf{g}_w$ [kg/(m² · s)] is the vapor flux due to diffusion.

• Moisture transport:

$$M_v \mathbf{u} \cdot \nabla C_v + \nabla \cdot (-M_v D \nabla C_v) = R \quad (5)$$

$$C_v = \phi C_{sat}(T) \quad (6)$$

where M_v [kg/mol] is the molar mass of water vapor, ϕ is the local relative humidity, C_{sat} [mol/m³] is the saturation vapor concentration, D [m²/s] is the diffusion coefficient of vapor in air, and R [kg/(m³ · s)] is the moisture source.

• Surface-to-surface radiation:

Thermal radiation is exchanged among the rear surface of the PV cells, the water surface, and the surrounding surfaces according to their respective view factors. The radiative view factors are determined by the geometry and relative orientation of the participating surfaces [34]. The net radiative heat fluxes at the rear surface of the PV cells and the water surface are expressed as follows:

$$q_{rad,PV} = \frac{\epsilon_1}{1 - \epsilon_1} (E_{b1} - J_1) \quad (7)$$

$$q_{rad,w} = \frac{-\epsilon_2}{1 - \epsilon_2} (E_{b2} - J_2) \quad (8)$$

These radiative heat fluxes are coupled to other physical fields and contribute to the source term in the energy equation. Here, ϵ is the longwave emittance of each surface; $E_b = \sigma T^4$ [W/m²] is the blackbody emissive power at temperature T ; $\sigma = 5.67 \times 10^{-8}$ [W/(m² · K⁴)] is the Stefan-Boltzmann constant; and J is the radiosity of each surface. Subscripts 1, 2, and 3 refer to the rear surface of the PV cells, the water surface, and the surrounding environment, respectively.

The radiosities can be solved using the set of radiosity-irradiation balance equations:

$$\begin{aligned} J_1 &= \epsilon_1 E_{b1} + (1 - \epsilon_1) (J_1 F_{11} + J_2 F_{12} + J_3 F_{13}) \\ J_2 &= \epsilon_2 E_{b2} + (1 - \epsilon_2) (J_1 F_{21} + J_2 F_{22} + J_3 F_{23}) \\ J_3 &= \epsilon_3 E_{b3} + (1 - \epsilon_3) (J_1 F_{31} + J_2 F_{32} + J_3 F_{33}) \end{aligned} \quad (9)$$

where F_{ij} is the view factor from surface i to surface j [35]:

$$\begin{aligned} F_{ij} = \frac{2}{\pi \bar{X} \bar{Y}} \left\{ \ln \left[\frac{(1 + \bar{X}^2)(1 + \bar{Y}^2)}{1 + \bar{X}^2 + \bar{Y}^2} \right]^{1/2} + \bar{X} \sqrt{1 + \bar{Y}^2} \tan^{-1} \left(\frac{\bar{X}}{\sqrt{1 + \bar{Y}^2}} \right) \right. \\ \left. + \bar{Y} \sqrt{1 + \bar{X}^2} \tan^{-1} \left(\frac{\bar{Y}}{\sqrt{1 + \bar{X}^2}} \right) - \bar{X} \tan^{-1} \bar{X} - \bar{Y} \tan^{-1} \bar{Y} \right\} \end{aligned} \quad (10)$$

where $\bar{X} = L/a$ and $\bar{Y} = W/a$ denote the ratios of the PV component's length and width, respectively, to the air-gap thickness a . In this study, both the PV cells and the water surface are assumed to be square; hence, $\bar{X} = \bar{Y}$, as illustrated in Fig. 6(a). Fig. 6(b) further shows that the view factor decreases as the air-gap thickness increases, indicating weaker radiative heat transfer across larger gaps.

The reciprocity relationship for the view factors is valid, i.e., $A_i F_{ij} = A_j F_{ji}$. For this three-surface system (PV, water, and surroundings), the summation rule gives $F_{13} = 1 - F_{12}$.

2.3.2. Boundary conditions

The boundary conditions adopted in the model are illustrated in Fig. 7. For airflow, a uniform inlet speed u is prescribed at the inlet of the external air domain, while the remaining lateral and upper boundaries are treated as open boundaries at ambient pressure. All solid surfaces exposed to the airflow are treated as no-slip walls.

For moisture transport, the vapor concentration at the inlet is determined from the ambient temperature and relative humidity. The remaining lateral and upper boundaries are treated as open boundaries. The upper surface of the thin water layer is prescribed as a wet evaporating boundary at the local saturation vapor concentration, and the associated latent heat transfer is coupled to the energy equation. All other bottom and solid boundaries are treated as impermeable.

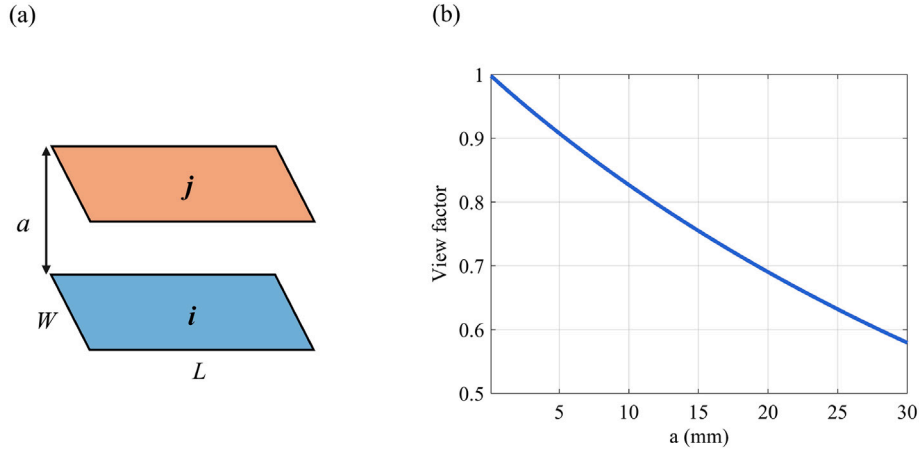


Fig. 6. (a) Radiation exchange between aligned parallel plates; (b) Dependence of the radiation view factor on the gap thickness when $L = W = 10$ cm.

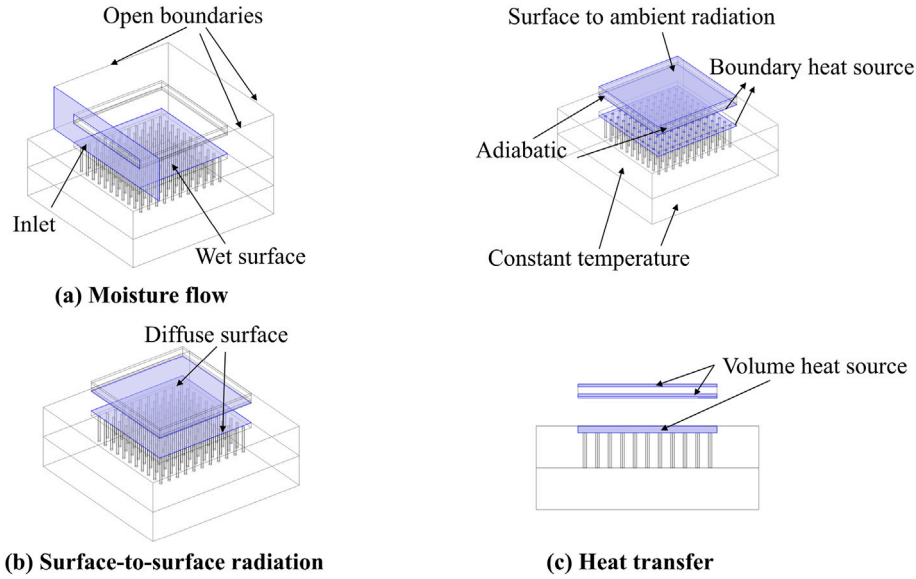


Fig. 7. Boundary conditions of the 3-D numerical model: (a) moisture flow, (b) surface-to-surface radiation, and (c) heat transfer.

The surfaces participating in surface-to-surface radiative exchange are shown in Fig. 7(b), while the principal thermal boundary conditions are illustrated in Fig. 7(c). Radiative exchange between the rear surface of the PV cells and the water surface is incorporated into the heat-transfer model, as described in Section 2.3.1. The upper surface of the convection cover exchanges longwave radiation with the sky. Under clear-sky conditions, the equivalent sky temperature, T_{sky} , is calculated using the Brunt empirical correlation [36]:

$$T_{\text{sky}} = \left[0.55 + 1.8 \left(\frac{\phi_{\text{amb}} P_{\text{sat}}(T_{\text{amb}})}{P} \right)^{1/2} \right]^{1/4} T_{\text{amb}} \quad (11)$$

Here, ϕ_{amb} is the ambient relative humidity, $P_{\text{sat}}(T_{\text{amb}})$ is the saturation vapor pressure at the absolute ambient temperature T_{amb} , and P is the atmospheric pressure. The lateral surfaces of the PV component and the convection cover are treated as adiabatic to represent the insulated sides of the device. The outer boundaries of the bulk-water domain are maintained at T_{amb} . The same temperature is prescribed at the external surfaces of the floating insulation to represent thermal coupling with the surrounding bulk water. A complete specification of the boundary conditions and an assessment of the simplified thermal boundary representations are provided in Appendix A.4.

The boundary and volumetric heat sources are also indicated in Fig. 7(c). The fraction of solar energy absorbed by the PV cells that is not converted into electricity is applied to the PV surface as a boundary heat flux. Solar radiation absorbed by the glass layers of the convection cover and PV component is represented as volumetric heat generation within the corresponding glass domains. For the STPV device, the solar radiation transmitted toward the water is divided into two wavelength ranges based on the absorption and scattering characteristics of water. Radiation at wavelengths greater than 1320 nm is absorbed within the 5-mm-thick water layer and is represented as a volumetric heat source, whereas radiation at shorter wavelengths is absorbed at the upper surface of the floating insulation. The corresponding heat source terms are defined below.

2.3.3. Distribution of solar energy within the system

• Glass component:

Solar irradiance reaching the glass is mostly transmitted, while the rest is reflected or absorbed, depending on the optical properties of the glass. The energy absorbed is converted into a heat source for the glass layer, which is calculated as [33]:

$$Q_{\text{abs,g}} = \int_{280}^{\infty} G_{\text{sun}}(\lambda) \alpha_g d\lambda \quad (12)$$

where α_g is the absorptance of the glass, $G_{\text{sun}}(\lambda)$ is the spectral solar irradiance incident on the Earth's surface, as plotted in Fig. 4(a).

• *PV component:*

The incident spectral solar irradiance on the PV cell depends on the transmittance of the glass τ_g , and is given by:

$$G_{\text{PV}}(\lambda) = G_{\text{sun}}(\lambda)\tau_g^2 \quad (13)$$

The solar energy absorbed by the PV cells is calculated as follows:

$$Q_{\text{abs,PV}} = \int_{280}^{\infty} G_{\text{PV}}(\lambda)(1 - R_{\text{PV}} - \tau_{\text{PV}}(\lambda))d\lambda \quad (14)$$

where $\tau_{\text{PV}}(\lambda)$ is the spectral transmittance of the STPV cells, whose spectra are illustrated in Fig. 4(b). For the c-Si cell, the transmittance is zero. R_{PV} is the solar-spectrum-averaged reflectance of the PV cells.

The PV cells convert a portion of the absorbed solar energy into electricity, with a temperature-dependent conversion efficiency:

$$\eta_{\text{el}} = \eta_{\text{el},0} [1 + \beta (T_{\text{PV}} - T_{\text{ref}})] \quad (15)$$

where $\eta_{\text{el},0}$ is the electrical efficiency at $T_{\text{ref}} = 25^\circ\text{C}$, β is the temperature coefficient of the PV cells and T_{PV} is the actual operating temperature of the PV cells. The electrical power density generated by the PV cells is then calculated as [37]:

$$P_{\text{PV}} = \eta_{\text{el}} \cdot \int_{280}^{\infty} G_{\text{PV}}(\lambda)d\lambda \quad (16)$$

In particular, the heat generated in the PV cells depends not only on the energy absorbed $Q_{\text{abs,PV}}$ but also on the electrical performance of the PV cells. The residual heat generated in the PV cells is then calculated as:

$$Q_{\text{h,PV}} = Q_{\text{abs,PV}} - P_{\text{PV}} \quad (17)$$

• *Water component:*

For an opaque c-Si cell, no photons reach the water surface directly. For STPV cells, the solar energy transmitted through the glass layers and the cells that reaches the water surface is as follows:

$$G_{\text{w}}(\lambda) = G_{\text{PV}}(\lambda)\tau_{\text{PV}}(\lambda) \quad (18)$$

Since the absorption coefficient of water is strongly wavelength-dependent (Fig. 3), the transmitted radiation is divided into two parts according to the optical response of the 5 mm water layer. Radiation with wavelengths above 1320 nm is assumed to be absorbed within the thin water layer and is treated as a volumetric heat source:

$$Q_{\text{abs,b}} = \int_{1320}^{\infty} G_{\text{w}}(\lambda)d\lambda \quad (19)$$

The shorter-wavelength photons are mainly absorbed by the photothermal coating on the floating insulation, which is modeled as a surface heat flux:

$$Q_{\text{abs,ins}} = \alpha_{\text{ins}} \cdot \int_{280}^{1320} G_{\text{w}}(\lambda)d\lambda \quad (20)$$

The optical and electrical properties of the components are summarized in Table 2. The absorbed heat fluxes, $Q_{\text{abs,g}}$ and $Q_{\text{abs,b}}$, are divided by the thicknesses of their respective domains and applied as uniform volumetric heat sources in the glass and water domains, respectively. The coupled governing equations, boundary conditions, and heat source terms are solved using the finite element method in COMSOL Multiphysics 6.2 to obtain the temperature field and evaporation rate. The grid-independence analysis and model validation are presented in Appendices A.2 and A.3, respectively. The sensitivity of the predicted efficiencies to selected model inputs is assessed in Appendix A.5.

Table 2

Optical and electrical properties of the components in the PV–CLE integrated system.

Component	Property	Value	Reference
Convection cover outer surface	Emittance, ϵ_c	0.04	[26]
Glass layer	Absorptance, α_g	0.01	[38]
Glass layer	Transmittance, τ_g	0.96	[39]
STPV cells	Transmittance, τ_{PV}	Fig. 4	[29,30]
PV cell	Average reflectance, R_{PV}	0.07	[38,40]
Coated rear surface of PV	Emittance, ϵ_{PV}	0.94	[23]
Water surface	Emittance, ϵ_w	0.95	[41]
Top surface of insulation	Absorptance, α_{ins}	0.99	[28]
c-Si cell	Electrical efficiency, $\eta_{\text{el},0}$	23%	[42]
	Temperature coefficient, β	$-0.29\% \text{ K}^{-1}$	
CdTe cell	Electrical efficiency, $\eta_{\text{el},0}$	8.6%	[29]
	Temperature coefficient, β	$-0.25\% \text{ K}^{-1}$	
PSC cell	Electrical efficiency, $\eta_{\text{el},0}$	15.7%	[30]
	Temperature coefficient, β	$-0.17\% \text{ K}^{-1}$	

2.4. Performance assessment metrics

The useful outputs of the solar-driven integrated system consist of electricity and water vapor. Consequently, the performance of the hybrid system is first characterized by the solar-to-electricity efficiency and the solar-to-vapor efficiency [11]:

$$\eta_e = \frac{P_{\text{PV}}}{\int_{280}^{\infty} G_{\text{sun}}(\lambda)d\lambda} \quad (21)$$

$$\eta_v = \frac{\dot{m}h_{\text{fg}}}{\int_{280}^{\infty} G_{\text{sun}}(\lambda)d\lambda} \quad (22)$$

where $\dot{m}$ [$\text{kg}/(\text{m}^2 \cdot \text{s})$] represents the evaporation rate, and h_{fg} [J/kg] is the enthalpy of water vaporization.

To enable a unified evaluation of solar systems with different energy outputs, an equivalent energy framework is adopted. The overall equivalent efficiency is defined as

$$\eta_o = \eta_v + w\eta_e \quad (23)$$

where w is a weighting factor that converts electricity into equivalent thermal energy. Depending on the evaluation criterion, w may be defined based on the relative thermodynamic, economic, or environmental values of two [43] or more [44] energy outputs. In this study, w is set to $(0.38)^{-1} = 2.63$, based on the reference electricity generation efficiency of conventional thermal power plants (38%) [14]. The resulting metric allows the vapor and electrical outputs to be evaluated on a common equivalent energy basis.

3. Results and discussion

In this section, steady-state simulations are performed using the 3-D numerical model to quantify and compare the performance of three PV technologies under various operating conditions. The baseline case uses pure water, a 5-mm air gap between the PV component and the water surface, an ambient temperature of 25°C , a relative humidity of 50%, a wind speed of 0.3 m/s, and one sun illumination (1000 W m^{-2}). First, the distribution of solar energy within the system is examined based on the optical properties of the different PV components. Subsequently, the effects of ambient conditions and air-gap thickness on the evaporation rate, electrical output, and overall system performance are systematically evaluated. The three PV–CLE configurations are then compared with the absorber-only CLE reference in terms of temperature, efficiency, and energy-flow characteristics to elucidate

their performance differences. This comparison is further extended to seawater and concentrated-brine conditions by considering the effect of salinity. Finally, the proposed systems are benchmarked against representative CLE and PV-enabled cogeneration systems reported in the literature.

3.1. Solar energy allocation

To understand the differences in thermal response, solar-to-electricity efficiency, evaporation behavior, and overall equivalent efficiency discussed in the following sections, it is first necessary to determine how each PV technology partitions the incident solar energy within the PV–CLE architecture. In this integrated system, the PV cell functions not only as an electricity generator but also as a solar absorber that governs the fractions of incident irradiation converted into electricity, dissipated as residual heat, and transmitted to the evaporation side. The allocation of solar energy therefore provides a mechanistic basis for understanding the distinct system-level behavior of the different PV–CLE configurations.

In the c-Si–CLE system, the opaque c-Si cell spatially separates the solar absorption region from the evaporation zone and serves as both the photovoltaic conversion layer and the solar absorber. Unlike conventional absorber-based CLE systems, in which the absorbed solar energy is entirely converted into heat, the PV cell converts a portion of the incident solar energy into electricity. Because of its limited photovoltaic conversion efficiency, the remaining absorbed energy is dissipated as heat, thereby increasing the cell temperature. Longwave radiation emitted from the rear surface of the cell is subsequently absorbed within the upper $\sim 100\ \mu\text{m}$ of the water layer, thus driving interfacial evaporation. After accounting for optical losses, including reflection and absorption by the glass layers, the incident solar energy in the c-Si–CLE cogeneration system is partitioned primarily into electricity and residual heat in the PV cell, as shown in Fig. 8. Under the baseline conditions, approximately 19.2% of the incident solar energy is converted into electricity, whereas approximately 66.5% remains as residual heat in the PV cell and subsequently contributes to thermal losses and radiative heating of the water.

By contrast, in the STPV–CLE systems, the STPV cells function not only as photovoltaic devices but also as spectral splitters, selectively absorbing a portion of the incident spectrum with photon energies above the band gap while transmitting a substantial fraction of the longer-wavelength radiation to the underlying water. Part of the absorbed energy is converted into electricity, whereas the remainder is dissipated, convectively and radiatively, as residual heat. Owing to the wavelength-dependent absorption of water, only a portion of the transmitted solar spectrum is absorbed within the 5-mm-thick water layer. The remaining radiation is absorbed by the photothermal material embedded in the floating insulation and is subsequently transferred to the water layer as heat. Thus, the incident solar energy in an STPV–CLE system

is partitioned into four principal components: electrical output, residual PV heat, direct absorption by the water layer, and absorption by the photothermal material. The relative magnitudes of these components are determined by the optical and electrical characteristics of the PV technology.

For the PSC–CLE system, 43.9% of the incident solar energy is absorbed by the PSC cells, of which 14.0% of the incident energy is converted into electricity, and 29.9% remains as residual PV heat. In addition, 9.1% of the incident solar energy is absorbed directly by the water layer, and 32.7% is absorbed by the photothermal material after transmission through the PSC cells. By comparison, the CdTe cells transmit 47.9% of the incident solar energy because of their higher transmittance in the 600–750 nm wavelength range. However, only 7.6% of the incident solar energy is converted into electricity, whereas 30.3% remains as residual PV heat, a fraction comparable to that of the PSC cells. The optical loss is identical for all three systems (14.3%), indicating that the differences in solar-energy allocation arise primarily from variations in photovoltaic conversion and spectral partitioning.

More importantly, the three systems differ not only in their allocation of incident solar energy but also in the pathways through which energy is supplied for water evaporation. In the opaque c-Si–CLE system, the evaporation region is heated predominantly by residual PV heat transferred across the air gap through thermal radiation, conduction, and convection. In the semi-transparent PSC–CLE and CdTe–CLE systems, by contrast, the evaporation region receives energy through two parallel pathways: indirect heating by residual PV heat and direct optical heating through the absorption of transmitted solar radiation by the water layer and the photothermal material. These differences in primary energy partitioning and heating pathways result in distinct temperature distributions, electrical and evaporation performance, and overall equivalent efficiencies among the three PV–CLE systems.

3.2. Effects of environmental and geometrical factors on system performance

3.2.1. Effect of ambient temperature

Evaporation performance is governed primarily by the vapor pressure difference between the water surface and the ambient air, and is therefore highly sensitive to ambient temperature. The ambient temperature also affects the external thermal boundary conditions by altering the temperature gradients that drive heat dissipation from both the PV cells and the evaporation unit. To elucidate these effects, the performance of the three PV–CLE systems is evaluated over an ambient-temperature range of 10–50 °C.

As shown in Fig. 9(a), the PV cell and water surface temperatures increase monotonically with ambient temperature in all three systems. This trend is attributed primarily to the smaller temperature differences between the system and its surroundings under warmer ambient conditions, which reduce convective and radiative heat losses and allow a larger fraction of the absorbed solar energy to be retained within the system. Although the three systems exhibit similar temperature trends, clear differences are observed in their absolute temperature levels. Among them, the c-Si–CLE system maintains the highest PV cell temperature and the lowest water surface temperature throughout the investigated range. This behavior arises because approximately 20% of the incident solar energy is converted into electricity by the c-Si cell, while most of the remaining absorbed energy is dissipated as heat within the cell. Consequently, energy is delivered to the water surface primarily through secondary radiative and convective heat transfer from the PV cell across the air gap, which is constrained by the radiative view factor and the convective heat transfer coefficient.

By contrast, the CdTe–CLE and PSC–CLE systems exhibit substantially lower PV cell temperatures and higher water surface temperatures because a portion of the incident solar energy is transmitted directly to the underlying water. Their temperature distributions are generally similar, although the CdTe–CLE system exhibits slightly higher PV cell and

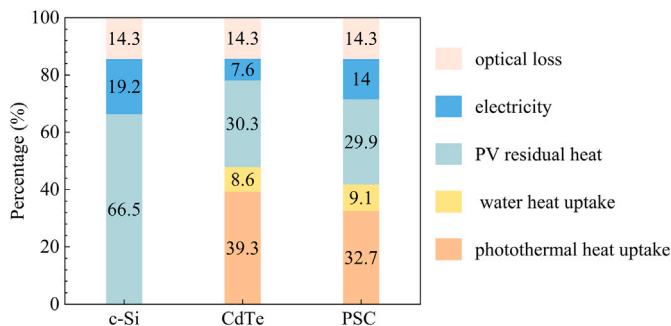


Fig. 8. Solar energy allocation in the three PV–CLE cogeneration systems.

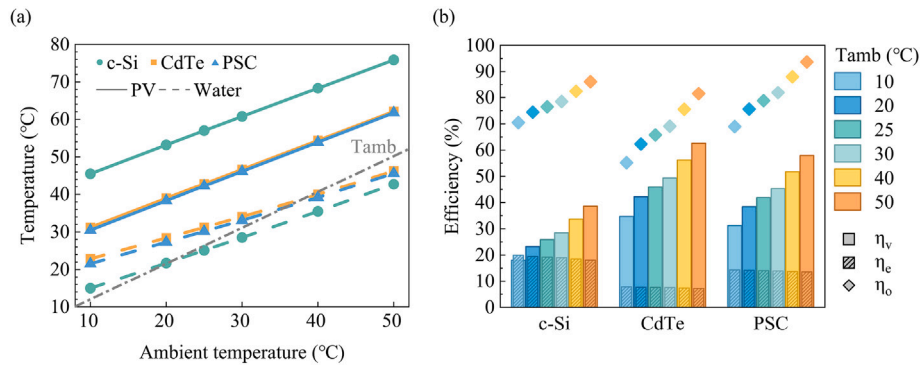


Fig. 9. Effect of ambient temperature on the performance of the three proposed systems under fixed operating conditions ($a = 5$ mm, $\phi_{amb} = 0.5$, $u = 0.3$ m/s): (a) PV cell and water surface temperatures, (b) efficiencies.

water surface temperatures than the PSC-CLE system. This difference is attributable to the lower photovoltaic efficiency of the CdTe cell, which leaves more residual energy to be dissipated as heat, as well as its higher transmittance, which allows more solar energy to reach the evaporation side directly.

Another notable feature in Fig. 9(a) is the crossover between the water surface and ambient temperatures. As the ambient temperature increases, the water surface temperature eventually falls below the ambient temperature because of the strong latent heat loss associated with evaporation. This crossover occurs near 25 °C for the c-Si-CLE system but shifts to approximately 40 °C for the PSC-CLE and CdTe-CLE systems, with the CdTe-CLE system exhibiting a slightly higher crossover temperature. The delayed crossover in the STPV systems indicates a greater ability to sustain interfacial heating under intensified evaporation, further demonstrating the advantage of direct optical heating in STPV-based configurations.

The corresponding variations in solar-to-electricity efficiency, solar-to-vapor efficiency, and overall equivalent efficiency are shown in Fig. 9(b). As the ambient temperature increases, the solar-to-electricity efficiency, η_e , decreases slightly in all three systems due to the increase in the operating temperature of the PV cells. The c-Si-CLE system exhibits the largest decline, from 20.0% to 18.0%, whereas the efficiencies of the CdTe-CLE and PSC-CLE systems decrease from 7.8% to 7.2% and from 14.3% to 13.6%, respectively. The greater deterioration in the c-Si-CLE system results from its substantially higher operating temperature, which is approximately 15 °C above those of the STPV systems, along with its larger temperature coefficient.

In contrast, the solar-to-vapor efficiency increases continuously with ambient temperature in all three systems. This enhancement reflects both the increase in the vapor pressure driving force for evaporation and the reduction in heat loss to the surroundings, which allow a larger fraction of the absorbed energy to be utilized for phase change. Consequently, η_v consistently follows the order CdTe-CLE > PSC-CLE > c-Si-CLE, confirming that the STPV configurations direct solar energy toward evaporation more effectively than the opaque c-Si configuration.

When both the quantity and quality of the energy outputs are considered, the improvement in evaporation performance outweighs the temperature-induced reduction in photovoltaic efficiency, resulting in a monotonic increase in the overall equivalent efficiency with ambient temperature for all three systems. However, this increase is smaller for the c-Si-CLE system than for the PSC-CLE and CdTe-CLE systems. This difference arises because evaporation in the c-Si-CLE system relies primarily on indirect heating by residual PV heat, which limits the extent to which improved heat retention can enhance evaporation. By contrast, the PSC-CLE and CdTe-CLE systems benefit from direct optical heating, enabling greater improvements in overall performance under warmer ambient conditions.

At 50 °C, the overall equivalent efficiency reaches 86.2% for the c-Si-CLE system and 93.7% for the PSC-CLE system. Despite exhibiting the highest solar-to-vapor efficiency, the CdTe-CLE system has a lower overall equivalent efficiency than the PSC-CLE system due to its lower electrical output. Consequently, the overall equivalent efficiency of the PSC-CLE system is slightly lower than that of the c-Si-CLE system at $T_{amb} = 10$ °C, but it becomes increasingly advantageous as the ambient temperature rises. Meanwhile, the difference between the c-Si-CLE and CdTe-CLE systems gradually decreases. These results demonstrate that the preferred PV technology depends on climatic conditions because of the trade-off among electrical output, evaporation enhancement, and ambient thermal conditions.

3.2.2. Effect of relative humidity

Relative humidity primarily affects evaporation by reducing the mass-transfer driving force. According to Fick's law, as the ambient relative humidity increases from 20% to 90%, the vapor concentration in the surrounding air increases, thereby reducing the concentration gradient between the water surface and the ambient air, and suppressing vapor diffusion away from the interface. Fig. 10 shows the corresponding effects on the temperatures and efficiencies of the three PV-CLE systems.

As shown in Fig. 10(a), increasing the relative humidity raises both the PV cell temperature and the water surface temperature in all three systems, with a more pronounced increase at the water surface. This trend arises because suppressed evaporation reduces latent heat removal from the interface, allowing more absorbed energy to accumulate in the evaporation layer. The resulting increase in water surface temperature reduces the temperature difference between the PV cells and the water surface, slightly weakening radiative heat transfer and causing a modest increase in PV cell temperature. Over the investigated humidity range, the water surface temperature increases by approximately 6.5–8 °C, whereas the corresponding increase in PV cell temperature is only about 2.7 °C. This difference indicates that relative humidity affects the evaporation process more strongly than the photovoltaic conversion process. Although all three systems exhibit the same qualitative trend, their absolute temperature levels remain distinct. The c-Si-CLE system maintains the highest PV cell temperature and the lowest water surface temperature, whereas the CdTe-CLE and PSC-CLE systems maintain lower PV cell temperatures and higher water surface temperatures because a portion of the incident solar energy is transmitted directly to the evaporation side.

The efficiency variations shown in Fig. 10(b) further confirm that relative humidity primarily affects evaporation. The solar-to-electricity efficiencies of the three systems remain nearly unchanged over the investigated humidity range because the humidity-induced increase in PV cell temperature is limited. By contrast, their solar-to-vapor efficiencies decrease by approximately 10.3–12.3 percentage points. This

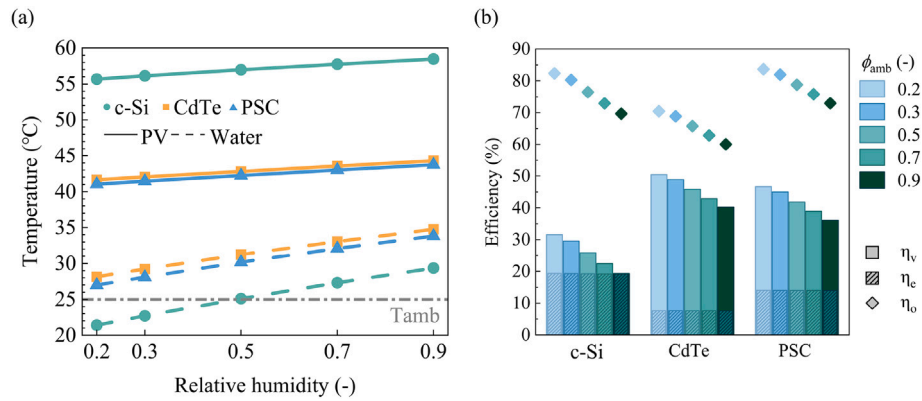


Fig. 10. Effect of relative humidity on the performance of the three proposed systems under fixed operating conditions ($a = 5$ mm, $u = 0.3$ m/s, $T_{amb} = 25$ °C): (a) PV cell and water surface temperatures, (b) efficiencies.

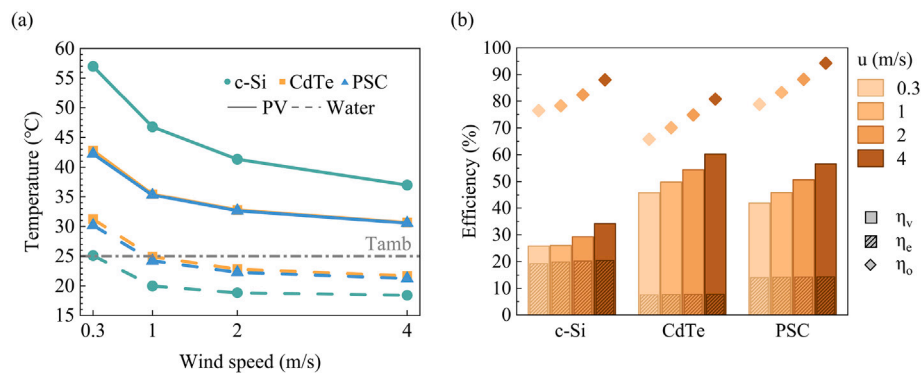


Fig. 11. Effects of wind speed on the performance of the three proposed systems under fixed operating conditions ($a = 5$ mm, $\phi_{amb} = 0.5$, and $T_{amb} = 25$ °C): (a) PV cell and water surface temperatures and (b) efficiencies.

contrast indicates that, under humid conditions, air-side mass transfer rather than energy supply becomes the dominant limitation. Specifically, increasing the ambient relative humidity reduces the vapor pressure difference between the evaporating surface and the surrounding air, thereby suppressing vapor transport and lowering the evaporation rate.

The responses of the three PV technologies under humid conditions also reveal distinct performance trade-offs. The CdTe-CLE system maintains the highest solar-to-vapor efficiency because its greater spectral transmittance delivers more solar energy directly to the evaporation side, thereby sustaining a relatively high interfacial temperature even when the vapor pressure driving force is reduced. The PSC-CLE system exhibits slightly lower evaporation performance than the CdTe-CLE system; however, its substantially higher electrical output enables it to maintain the highest overall equivalent efficiency throughout the investigated humidity range. By contrast, the c-Si-CLE system is more vulnerable to humid conditions because its evaporation side relies primarily on indirect heating by residual PV heat and is therefore less able to compensate for the humidity-induced reduction in the mass transfer driving force.

Consequently, the overall equivalent efficiencies of the three systems decrease monotonically by approximately 10.4–12.7 percentage points, primarily due to the deterioration in solar-to-vapor efficiency rather than any substantial reduction in photovoltaic conversion. Nevertheless, the PSC-CLE system consistently provides the best balance between electricity generation and evaporation enhancement. Its higher electrical output partially offsets the humidity-induced decline in solar-to-vapor efficiency, allowing it to retain an overall equivalent efficiency of approximately 73% even at a relative humidity of 90%.

3.2.3. Effect of wind speed

Wind introduces coupled and competing effects in PV-CLE systems by enhancing convective heat loss from the PV cells and water surface while facilitating vapor removal from the evaporation interface. To clarify this interplay under wind-driven mixed convection conditions, four representative wind speeds of 0.3, 1, 2, and 4 m/s are considered.

As shown in Fig. 11(a), increasing the wind speed substantially decreases both the PV cell and water surface temperatures due to enhanced convective cooling. The c-Si-CLE system exhibits the strongest temperature response due to its relatively high PV cell operating temperature and greater reliance on indirect heating for evaporation, which makes it more susceptible to wind-induced cooling. As the wind speed increases, the temperature differences among the three systems gradually decrease, with the CdTe-CLE and PSC-CLE systems approaching nearly identical PV cell and water surface temperatures. In addition, the water surface temperature of the c-Si-CLE system remains consistently lower than those of the two STPV-CLE systems, indicating a weaker thermal driving force for evaporation. At higher wind speeds, the water surface temperature of the c-Si-CLE system falls below the ambient temperature, whereas the direct transmission of solar energy in the CdTe-CLE and PSC-CLE systems partially offsets the cooling induced by airflow.

Fig. 11(b) shows that wind enhances electrical conversion by reducing the PV cell operating temperature. Consequently, the solar-to-electricity efficiency of all three systems increases with wind speed. Despite its relatively high operating temperature, the c-Si-CLE system maintains the highest η_e because of its superior intrinsic photovoltaic conversion performance, followed by the PSC-CLE and CdTe-CLE systems.

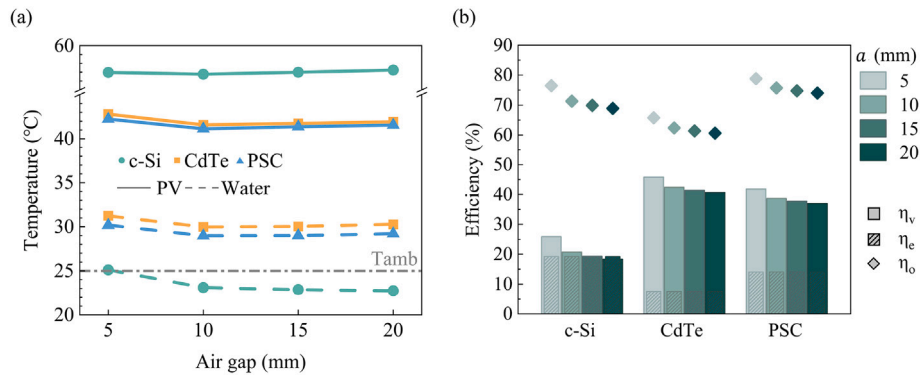


Fig. 12. Effects of air-gap thickness on the performance of the three proposed systems under fixed operating conditions ($u = 0.3$ m/s, $T_{amb} = 25$ °C, and $\phi_{amb} = 0.5$): (a) PV cell and water surface temperatures and (b) efficiencies.

More importantly, increasing the wind speed results in lower water surface temperatures but higher solar-to-vapor efficiencies for all three systems, revealing a clear decoupling between the interfacial temperature and evaporation performance. This apparently counterintuitive behavior indicates that evaporation is governed not only by the interfacial temperature but also by vapor transport through the adjacent air domain. Specifically, stronger airflow limits vapor accumulation near the evaporating surface, reduces the thickness of the concentration boundary layer, and enhances convective mass transfer from the interface to the ambient air. The enhancement in convective mass transfer therefore outweighs the thermal penalty associated with interfacial cooling, resulting in a net increase in solar-to-vapor efficiency.

The distinct responses of the three systems further reflect their different thermal-buffering capabilities. The c-Si-CLE system is more sensitive to wind-induced cooling because its evaporation process relies more strongly on indirect heating and is therefore more vulnerable to convective heat loss. By contrast, the CdTe-CLE and PSC-CLE systems partially offset this cooling effect through the direct transmission of solar energy to the evaporation side. Consequently, the STPV-CLE systems maintain relatively high water surface temperatures and strong evaporation performance under windy conditions, while also benefiting from enhanced vapor removal. Accordingly, the solar-to-vapor efficiency follows the order CdTe-CLE > PSC-CLE > c-Si-CLE, consistent with the corresponding order of water-surface temperature.

The overall equivalent efficiencies of all three systems also increase with wind speed. Among them, the PSC-CLE system achieves the highest overall equivalent efficiency, reaching approximately 94.5% at 4 m/s, because of its favorable balance between electricity generation and evaporation enhancement. It therefore maintains the highest overall equivalent efficiency throughout the investigated wind speed range. At low wind speeds, however, the design of the air gap and ventilation pathway becomes increasingly important for limiting vapor accumulation and maintaining the driving force for vapor transport.

3.2.4. Effect of air-gap thickness

The air-gap thickness is a key design variable in PV-CLE systems because it simultaneously governs the thermal coupling between the PV cells and the water surface and the transport of vapor away from the evaporation interface. As shown in Fig. 12, increasing the air-gap thickness from 5 to 20 mm substantially alters the temperature distribution and system performance. In particular, the radiative view factor between the rear surface of the PV cells and the water surface decreases from 0.91 to 0.69 (Fig. 6(b)), indicating progressively weaker radiative coupling. Meanwhile, the enlarged gap reduces vapor confinement above the water surface and facilitates vapor removal from the evaporation interface. The net effect of air-gap thickness is therefore determined by the competition between weakened thermal coupling and enhanced vapor transport.

As shown in Fig. 12, the c-Si-CLE system exhibits the greatest sensitivity to air-gap thickness. As the gap increases from 5 to 20 mm, the water surface temperature decreases from 25.1 to 22.8 °C and eventually falls below the ambient temperature due to the weakened radiative heat transfer from the rear surface of the PV cell to the water surface. Correspondingly, the overall equivalent efficiency decreases from 76.5% at $a = 5$ mm to less than 70% at $a = 20$ mm. By contrast, the PV cell temperature and solar-to-electricity efficiency remain nearly unchanged at approximately 57 °C and 19.2%, respectively. These results indicate that evaporation in the c-Si-CLE configuration depends strongly on gap-mediated heat transfer.

The PSC-CLE and CdTe-CLE systems are less sensitive to variations in air-gap thickness. In both systems, the PV cell and water surface temperatures vary by only approximately 1 °C because a substantial fraction of the energy supplied to the evaporation side is delivered through transmitted solar radiation and is therefore less dependent on gap-mediated radiative heating. Nevertheless, the solar-to-vapor efficiency decreases with increasing air-gap thickness, from 41.8% to 37.2% for the PSC-CLE system and from 45.8% to 40.6% for the CdTe-CLE system. Their solar-to-electricity efficiencies remain nearly constant at approximately 14.0% and 7.6%, respectively. Consequently, the overall equivalent efficiency decreases from 78.8% to 73.9% for the PSC-CLE system and from 65.8% to 60.5% for the CdTe-CLE system. These results confirm that STPV-based systems are more tolerant of air-gap enlargement because direct optical heating of the evaporation side partially decouples evaporation from gap-dependent radiative heat transfer.

Among the three systems, the PSC-CLE configuration maintains the highest overall equivalent efficiency across the entire range of air-gap thicknesses, reflecting its favorable balance between electrical conversion and evaporation performance. More generally, the c-Si-CLE system is the most sensitive to air-gap thickness, whereas the STPV-based systems exhibit greater structural tolerance to gap enlargement. From a design perspective, reducing the air-gap thickness within the investigated range preserves stronger PV-to-water thermal coupling, particularly for opaque PV configurations. Accordingly, the 5-mm gap yields the highest overall equivalent efficiency for all three PV configurations. A representative transient analysis of the PSC-CLE system further demonstrates that this trend persists under time-varying day-time conditions (Appendix B.1). An air-gap thickness close to 5 mm is therefore preferred at the present device scale, subject to manufacturing tolerances and the maintenance of a stable water surface.

3.3. Comparison with the absorber-only CLE system

To further assess the advantages of the proposed PV-CLE cogeneration systems, the three PV-CLE configurations are compared with an absorber-only CLE system under identical solar input and baseline operating conditions. Unlike the absorber-only CLE system, which utilizes the

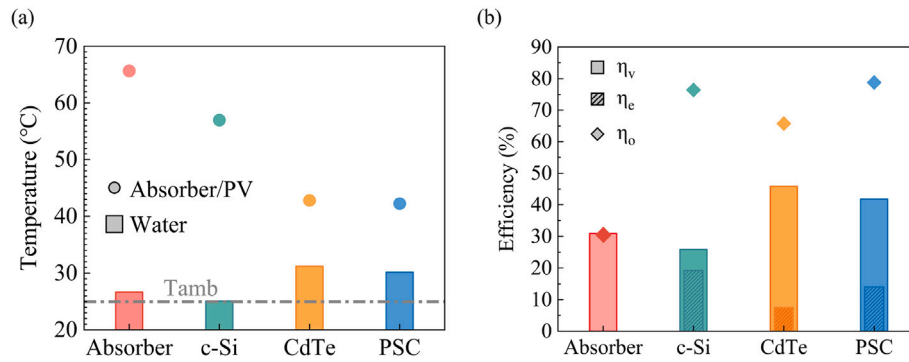


Fig. 13. Comparison of the absorber-only system and the three PV-CLE systems under the baseline conditions ($T_{amb} = 25^\circ\text{C}$, $\phi_{amb} = 0.5$, $u = 0.3$ m/s, and $a = 5$ mm): (a) PV cell/absorber and water surface temperatures and (b) efficiencies.

absorbed solar energy exclusively for evaporation, the PV-CLE configurations simultaneously generate electricity and vapor. More importantly, STPV devices with spectral-splitting capability enable the incident solar energy to be distributed more effectively between electrical generation and water evaporation.

3.3.1. Temperature distribution and system efficiencies

Fig. 13 compares the temperature distributions and efficiencies of the absorber-only reference and the three PV-CLE configurations under the baseline operating conditions. The absorber-only CLE system exhibits the highest absorber temperature, reaching 65.6°C , whereas the corresponding PV cell temperatures of the c-Si-CLE, CdTe-CLE, and PSC-CLE systems are approximately 57.0 , 42.8 , and 42.2°C , respectively. Nevertheless, the absorber-only CLE system does not exhibit the highest water surface temperature. Instead, the CdTe-CLE and PSC-CLE configurations attain higher water surface temperatures despite their lower PV cell temperatures because the transmitted solar radiation directly supplies energy to the underlying water and photothermal material. In the absorber-only CLE system, most of the incident solar energy is converted into heat within the upper absorber, resulting in pronounced thermal accumulation in the absorber layer. In the c-Si-CLE system, a portion of the incident solar energy is converted into electricity, thereby reducing heat generation and lowering the cell temperature relative to that of the absorber-only CLE system. This reduction is more pronounced in the STPV-based systems because the cells additionally transmit a portion of the incident solar radiation to the evaporation side. This spectral transmission suppresses heat accumulation within the PV layer while enhancing direct heating of the water and photothermal material.

The efficiency comparison further highlights the distinct roles of the three PV technologies. The absorber-only system achieves a solar-to-vapor efficiency of approximately 30.9%, but it produces no electricity. Among the PV-enabled systems, the solar-to-electricity efficiency follows the order c-Si-CLE > PSC-CLE > CdTe-CLE, which primarily reflects the intrinsic photovoltaic characteristics of the three technologies. The c-Si-CLE system achieves the highest solar-to-electricity efficiency, at 19.2%; however, its opaque structure prevents direct optical heating of the evaporation side, limiting its solar-to-vapor efficiency to approximately 25.9%. By contrast, the CdTe-CLE system achieves the highest solar-to-vapor efficiency, at 45.8% due to its high spectral transmittance, but its solar-to-electricity efficiency is relatively low, at 7.6%. The PSC-CLE system provides the most balanced performance, combining a solar-to-vapor efficiency of 41.8% with a solar-to-electricity efficiency of 14.0%. These results demonstrate that the principal benefit of PV integration lies in the coordinated allocation of incident solar energy between electricity generation and water evaporation rather than in maximizing either output independently.

All three PV-CLE systems outperform the absorber-only reference in terms of overall equivalent efficiency, indicating that incorporating a

PV component improves the utilization of solar energy by adding a high-quality electrical-output pathway to the evaporation system. The extent of this improvement, however, depends strongly on how effectively each PV technology balances photovoltaic conversion and spectral transmission to the evaporation side. Among the three PV-enabled configurations, the PSC-CLE system provides the most favorable balance, achieving an overall equivalent efficiency of 78.8%, compared with 30.9% for the absorber-only system. This difference corresponds to approximately a 155% relative improvement in the integrated performance metric.

3.3.2. Energy flow distribution

The Sankey diagrams in Fig. 14 summarize the energy flow distributions of the four systems at an air-gap thickness of 5 mm. In the absorber-only system, all absorbed solar energy is converted into thermal energy, which is intrinsically low grade. The resulting high absorber temperature causes substantial parasitic heat losses, including convective losses of 13.3% from the upper surface and 45.8% from the lower surface of the absorber. Although the elevated absorber temperature enhances radiative heat transfer to the water surface, which accounts for 23.8% of the total incident energy, a large fraction of the absorbed energy is dissipated rather than utilized for vapor generation. Moreover, because the narrow gap maintains the enclosed air at a higher temperature than the water surface (Fig. 15(a)), the water surface receives an additional convective heat input equivalent to 8.0% of the incident solar energy.

As shown in Fig. 14(b), introducing c-Si cells redirects a portion of the incident solar energy toward electricity generation, thereby reducing thermal accumulation within the cells. Accordingly, the c-Si cells operate at a temperature approximately 8.6°C lower than that of the absorber in the absorber-only CLE system. Because c-Si is optically opaque, however, most of the energy not converted into electricity remains as heat within the PV cells. Thermal losses therefore remain considerable, including convective losses of 10.1% from the upper surface and 35.7% from the lower surface of the PV component. Thus, the c-Si-CLE system improves the quality of the harvested energy by generating electricity but does not enhance evaporation relative to the absorber-only reference, resulting in a solar-to-vapor efficiency of 25.9%.

By contrast, the two STPV-CLE systems exhibit fundamentally different energy allocation pathways. Relative to the c-Si-CLE system, the spectral redistribution substantially increases the fraction of incident energy delivered directly to the evaporation region. Specifically, 47.9% of the incident solar energy is transmitted through the CdTe cells, increasing the water surface temperature by approximately 6°C relative to that of the c-Si-CLE system and raising the latent-heat fraction to 45.8%. However, the relatively low photovoltaic conversion efficiency of the CdTe cells limits their electrical output to 7.6%, thereby constraining the overall equivalent efficiency. In addition, because the water surface

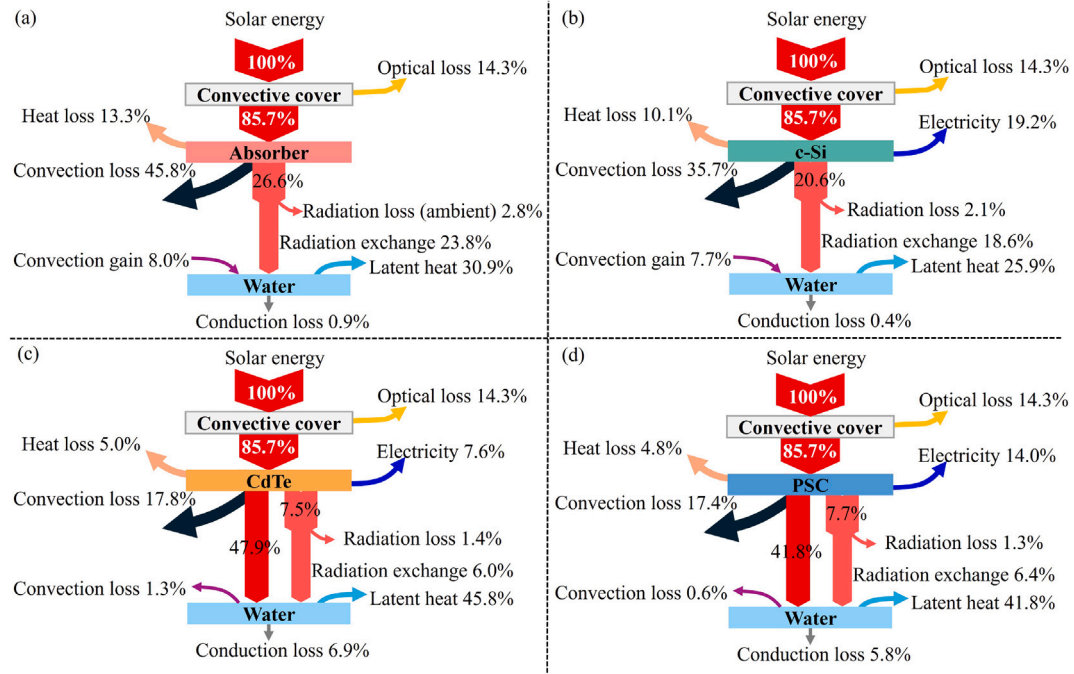


Fig. 14. Sankey diagrams showing the energy flow distributions of the four systems under the baseline conditions ($T_{\text{amb}} = 25^\circ\text{C}$, $\phi_{\text{amb}} = 0.5$, $u = 0.3$ m/s, and $a = 5$ mm): (a) absorber-only CLE, (b) c-Si-CLE, (c) CdTe-CLE, and (d) PSC-CLE.

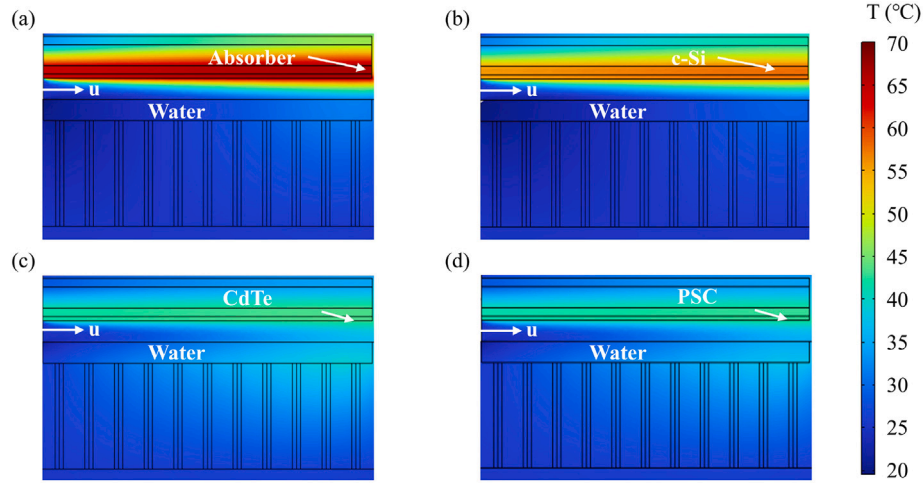


Fig. 15. Temperature distributions of the four systems under the baseline conditions ($T_{\text{amb}} = 25^\circ\text{C}$, $\phi_{\text{amb}} = 0.5$, $u = 0.3$ m/s, and $a = 5$ mm): (a) absorber-only, (b) c-Si-CLE, (c) CdTe-CLE, and (d) PSC-CLE.

temperature is slightly higher than the air temperature within the gap (Fig. 15(c)), the convective heat gain observed in the absorber-only and c-Si-CLE systems is eliminated.

The PSC-CLE system follows the same general energy-routing principle as the CdTe-CLE system but provides a more favorable balance between spectral transmission and electricity generation. Although the PSC cells have slightly lower optical transmittance, they achieve a substantially higher solar-to-electricity efficiency of 14.0% because of their greater intrinsic conversion capability and relatively low operating temperature. As shown in Fig. 14(d), 41.8% of the incident solar energy is delivered to the evaporation side through direct absorption by the water and photothermal material, which is lower than the corresponding fraction in the CdTe-CLE system. Consequently, the solar-to-vapor efficiency of the PSC-CLE system is approximately 4 percentage points lower than that of the CdTe-CLE system. Nevertheless, the PSC-CLE

system achieves the most balanced partitioning of incident solar energy between electricity generation and evaporation and therefore provides the highest overall equivalent efficiency among the four systems.

Collectively, these results demonstrate that PV integration improves overall solar energy utilization not only by introducing an electrical output pathway but also, in the case of STPV devices, by fundamentally redistributing where and how solar energy is utilized within the CLE architecture. The absorber-only CLE system concentrates the absorbed solar energy as heat within the upper absorber, whereas the STPV-CLE systems divide the incident energy between electricity generation and direct optical energy delivery to the evaporation region. This synergistic energy redistribution enables more effective utilization of the incident solar spectrum.

As presented in Appendix B.2, a 9-h transient analysis under representative daytime meteorological conditions further demonstrates that

Table 3

Performance of the absorber-only CLE and PV–CLE systems at different salinities under one-sun illumination.

System	η_v (%)			η_o (%)		
	0 wt%	3.5 wt%	10 wt%	0 wt%	3.5 wt%	10 wt%
Absorber-only CLE	30.9	30.5	29.7	30.9	30.5	29.7
c-Si–CLE	25.9	25.5	24.6	76.5	76.1	75.2
CdTe–CLE	45.8	45.5	44.4	65.8	65.4	64.4
PSC–CLE	41.8	41.4	40.5	78.8	78.4	77.4

all three PV–CLE systems maintain higher overall equivalent efficiencies than the absorber-only reference system, with the PSC–CLE system retaining the highest efficiency among the investigated PV technologies. The corresponding transient energy flows also preserve the distinct energy-transfer characteristics identified under steady-state conditions.

3.3.3. Performance at different salinity levels

The effect of salinity on evaporation is modeled using the water-activity correlation proposed by Nayar et al. [45]. Increasing salinity reduces water activity and, consequently, the equilibrium vapor pressure at the water surface, thereby weakening the driving force for evaporation. Uniform salinities of 3.5 and 10 wt% are prescribed to represent seawater and concentrated-brine conditions, respectively. The resulting system performance is summarized in Table 3. The salt management characteristics of the underlying CLE architecture are discussed separately in Section 3.4.2.

As salinity increases, η_v decreases moderately for all configurations because of the reduction in water activity, whereas η_e is affected only marginally. Consequently, η_o also decreases slightly with increasing salinity. At a salinity of 10 wt%, η_v decreases by 3.9%, 5.0%, 3.1%, and 3.1% for the absorber-only CLE, c-Si–CLE, CdTe–CLE, and PSC–CLE systems, respectively, relative to their corresponding pure-water values.

Nevertheless, the relative performance ranking of the four configurations remains unchanged. The CdTe–CLE system maintains the highest η_v , whereas the PSC–CLE system retains the highest η_o . In particular, the relative improvement in the overall equivalent efficiency of the PSC–CLE system over the absorber-only reference increases from approximately 155% under pure-water conditions to 157% and 161% at salinities of 3.5 and 10 wt%, respectively. This gradual increase in relative advantage occurs because salinity primarily suppresses vapor production, whereas the electrical contribution of the PSC–CLE system is only weakly affected.

3.4. Performance comparison and benchmarking

3.4.1. Comparison with previously reported CLE systems

To position the proposed systems within the current research landscape, the three PV–CLE configurations are benchmarked against representative state-of-the-art CLE systems reported in recent years. Previous CLE studies have focused primarily on maximizing solar-to-vapor efficiency through structural designs that improve thermal management and vapor transport. Accordingly, their performance has generally been evaluated solely in terms of vapor generation. By contrast, the present work incorporates electricity as an additional high-grade output, extending the comparison from a single evaporation-oriented metric to a more comprehensive assessment of solar energy utilization.

Fig. 16 compares the solar-to-vapor and overall equivalent efficiencies of the proposed systems with those of representative CLE systems reported in the literature. Because the previously reported CLE systems included in this comparison do not generate electricity, their overall equivalent efficiency reduces to their solar-to-vapor efficiency according to Eq. (23). The proposed PV–CLE systems therefore occupy a distinct position relative to conventional CLE designs because they generate both water vapor and electricity within the same device footprint.

Among the systems surveyed, the PSC–CLE and c-Si–CLE configurations achieve the two highest overall equivalent efficiencies, exceeding

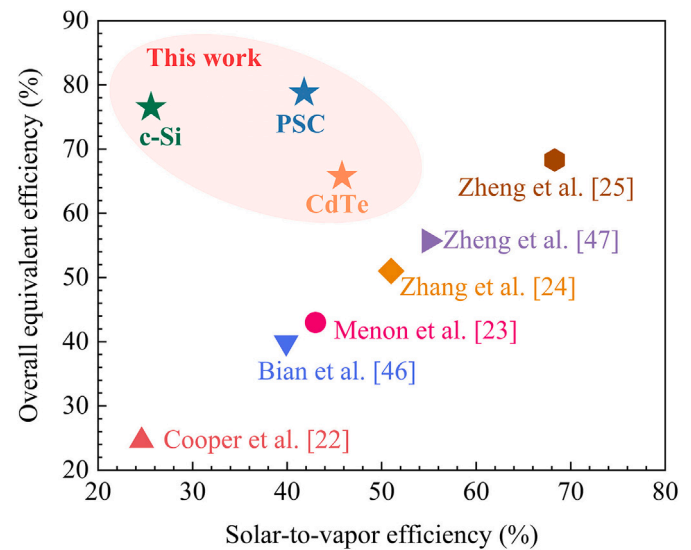


Fig. 16. Comparison of the solar-to-vapor and overall equivalent efficiencies of the proposed PV–CLE configurations with those of representative contactless solar evaporation systems reported in the literature [22–25,46,47]. For systems without electrical output, the overall equivalent efficiency is equal to the solar-to-vapor efficiency under the adopted evaluation framework.

those of the previously reported CLE platforms under the adopted evaluation framework. Most previous CLE studies reported solar-to-vapor efficiencies below 60%, although a recent system employing a complex three-dimensional vapor-release structure and a 1-mm air gap achieved a solar-to-vapor efficiency of 68.3% [25]. By integrating photovoltaic conversion into a wick-free contactless evaporation architecture, the proposed PV–CLE concept extends CLE from single-output vapor generation to the cogeneration of electricity and vapor. Under the adopted equivalent-energy metric, the PSC–CLE system achieves the highest calculated overall equivalent efficiency among the systems considered, reflecting the coordinated utilization of photovoltaic conversion, residual PV heat, and transmitted solar radiation.

3.4.2. Comparison with PV-enabled water–electricity cogeneration systems

Representative PV-enabled water–electricity cogeneration systems from the literature are compared in Table 4 in terms of PV technology, coupling configuration, number of stages, water-transport medium, salt-management strategy, and reported electrical and water-side performance. Existing designs include backside-coupled PV–membrane-distillation systems, semi-transparent-PV/interfacial-evaporation systems, and multistage configurations incorporating latent-heat recovery. Their electrical and water-production performance has been enhanced through strategies such as PV waste heat recovery, multistage recycling of condensation latent heat, spectral splitting, and front-side optical–thermal regulation. Despite these differences, most reported systems rely on capillary-fed porous media or wicking structures to transport saline water to the evaporation interface.

In these contact-based configurations, water delivery and salt transport occur within the same porous or wicking medium. Continuous evaporation increases the local salt concentration and therefore necessitates dedicated salt management strategies, including cross-flow, diffusion- or gravity-driven back-transport, intermittent rinsing, concentration-driven backflow, controlled crystallization, and anti-polyelectrolyte effects, as summarized in Table 4. In contrast, PV–CLE retains the wick-free confined-water-layer and macrochannel architecture introduced by Zhang et al. [24], while coupling it to an overhead PV component across an air gap. Salinity-induced natural convection through the macrochannels transports evaporation-concentrated brine back to the bulk-water reservoir, as demonstrated numerically and experimentally

Table 4
Salt management characteristics and performance of representative PV-enabled cogeneration systems from the literature.

Ref.	PV type	Contact	Stages	Water transport medium	Salt management mechanism	Salt resistance test	Salt behavior	Electrical performance, η_e	Evaporation performance*
Wang et al. [8]	Poly-Si	Yes	3	Quartz glass fibrous membrane (capillary)	Cross-flow by gravity or pump	Seawater; 3-day continuous test	Dead-end: accumulation; cross-flow: avoided	11.6%	1.79 kg m ⁻² h ⁻¹ (freshwater)
Huang et al. [48]	Mono-Si	Yes	4	Cotton wick (capillary)	Diffusion and gravity drainage	Seawater	Not evaluated	6.66%	1.11 kg m ⁻² h ⁻¹ (freshwater)
Xu et al. [49]	IR-transparent c-Si	Yes	1	r-GO-based absorber (capillary)	Salt diffusion/rejection	3.5 wt% salt water; >120 h	Not reported	20.4%	0.80 kg m ⁻² h ⁻¹ ; $\eta_v = 54.2\%$
Ji et al. [13]	Polymer cell	Yes	1	Cellulosic nonwoven fabric (capillary)	Salt diffusion	0.5 g salt-loading test; 75 min	Complete salt removal	12.2%	1.30 kg m ⁻² h ⁻¹
Yang et al. [15]	Si	Yes	5	Cellulose fiber (capillary)	Siphon-assisted intermittent rinsing	35–170 g/L NaCl; up to 20 h	Edge crystallization; subsequently rinsed	9.7%	1.71 kg m ⁻² h ⁻¹ (freshwater)
Wang et al. [50]	Si	Yes	5	Nonwoven fabric (capillary)	Cross-flow and controlled crystallization	Seawater; 6 daily cycles	Localized crystallization	13.9–14.0%	2.35–2.45 kg m ⁻² h ⁻¹ (freshwater)
Bai et al. [51]	Mono-Si	Yes	7	Paper towel (capillary)	Solute back-transport	groundwater, river water, and seawater; >30 h	No salt accumulation	17.44%	2.26 kg m ⁻² h ⁻¹
Liu et al. [11]	Mono-Si	Yes	5	Fibrous Janus membrane (capillary)	–	Water	Not reported	16.6%	3.39 kg m ⁻² h ⁻¹ (freshwater)
Chen et al. [14]	Semi-transparent Si	Yes	10	Paper towel (capillary)	Concentration-driven salt backflow at night	Seawater	Not evaluated	19.57%	3.17 kg m ⁻² h ⁻¹ ; $\eta_v = 210\%$
Liu et al. [52]	Mono-Si	Yes	9	Passive-wicking material (capillary)	Additional seawater outlet channel	Simulated seawater; >52 h	No crystallization observed	19.1%	4.27 kg m ⁻² h ⁻¹
Ye et al. [53]	Mono-Si	Yes	9	Fibrous Janus membrane (capillary)	Anti-polyelectrolyte effect	20 wt% NaCl; 10 h	Crystallization suppressed	15.3%	3.89 kg m ⁻² h ⁻¹ (freshwater)
PV-CLE [†] (this work)	c-Si CdTe PSC	No	1	Wick-free	Natural convection of saline water	Not tested; underlying CLE architecture validated in Refs. [24,25]	Not evaluated in this study	19.2% 7.6% 14.0%	$\eta_v = 25.9\%$ $\eta_v = 45.8\%$ $\eta_v = 41.8\%$

Note: All reported electrical and evaporation performances are based on one-sun illumination; salt-resistance conditions are listed separately. *Entries explicitly labeled as “freshwater” denote collected freshwater production, whereas unlabeled entries refer to water-vapor production. [†]Results for PV-CLE correspond to the baseline case.

in the original CLE study. That architecture operated with 25 wt% brine for 6 h without crystallization and with 20 wt% brine for one week without crystallization-induced fouling [24]. The same wick-free architecture was subsequently adopted by Zheng et al. [25], who demonstrated stable seawater evaporation over 60 h.

The performance data in Table 4 provide a comparative overview of these cogeneration architectures. The electrical efficiencies of the proposed PV–CLE configurations fall within the range reported in the representative systems. Several multistage systems achieve higher water-production rates and/or apparent solar-to-vapor efficiencies by repeatedly recovering latent heat. The distinguishing feature of the proposed PV–CLE is therefore not the maximization of water-side output, but the simultaneous production of electricity and water vapor without capillary-fed porous or wicking media. This wick-free configuration establishes water-transport, salt-management, and heat transfer pathways that are fundamentally different from those of conventional contact-based systems.

4. Conclusions

This study proposes a PV–CLE system for the solar-driven cogeneration of electricity and water vapor, in which the PV cells function simultaneously as electricity generators and as an upper solar absorber for evaporation. By physically separating the PV cells/absorber from the water, the contactless configuration prevents direct contact with brine and avoids the associated salt deposition on the PV cell/absorber surface. In systems incorporating STPV devices, the transmitted portion of the solar spectrum provides direct optical heating of the evaporation side, thereby promoting evaporation and enabling more effective utilization of the incident solar spectrum.

A coupled 3-D multiphysics model integrated with a spectral-splitting framework has been developed to quantify the electrical and evaporative performance of the PV–CLE system and to provide a design tool for such configurations. The effects of ambient temperature, relative humidity, wind speed, and air-gap thickness were systematically investigated, and three representative PV technologies, namely c-Si, CdTe, and PSC, were compared. The results demonstrate that higher ambient temperature, lower relative humidity, and higher wind speed generally improve the overall performance of the coupled system. Among the investigated air-gap thicknesses of 5–20 mm, the 5-mm gap yields the highest overall equivalent efficiency for all three PV configurations.

The three PV technologies exhibit distinct trade-offs between electrical generation and evaporation. The c-Si–CLE system achieves the highest solar-to-electricity efficiency (19.2%), but its solar-to-vapor efficiency (25.9%) is lower than that of the absorber-only reference (30.9%). The CdTe–CLE system achieves the highest solar-to-vapor efficiency (45.8%) because of its greater spectral transmittance, but it produces less electricity. By contrast, the PSC–CLE system provides the most balanced dual-output performance. Under the baseline conditions, it achieves an overall equivalent efficiency of 78.8%, compared with 30.9% for the absorber-only CLE reference system, corresponding to an approximately 155% relative improvement in this integrated metric. The STPV-based systems also maintain substantially lower PV cell operating temperatures than the opaque c-Si–CLE system.

Overall, the results demonstrate that the selection of PV technology for PV–CLE systems should account for the combined contributions of electricity generation and vapor production, rather than considering either output alone. The overall equivalent efficiency provides an integrated metric for comparing cogeneration performance, whereas the individual solar-to-electricity and solar-to-vapor efficiencies remain essential for technology selection under application-specific requirements. In particular, STPV technologies, especially the PSC-based configuration, provide a favorable balance between electricity generation and evaporation enhancement, enabling more effective utilization of the incident solar spectrum while maintaining lower PV cell temperatures than the c-Si configuration. These findings provide mechanistic insights

and practical design guidance for the further development of integrated solar-driven electricity–water-vapor cogeneration systems.

CRedit authorship contribution statement

Xin Wei: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Haoran Chang:** Software. **Qifeng Li:** Validation. **Wei Wu:** Writing – review & editing. **Christos N. Markides:** Writing – review & editing, Supervision, Project administration. **Mengying Li:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this article, the authors used GPT-5 to improve the language and readability. Following the use of these tools, the authors reviewed and edited the content as needed, taking full responsibility for the content of the publication as it appears in its present form.

Declaration of competing 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.

Acknowledgements

The authors gratefully acknowledge the substantial support from the Hong Kong University Grants Committee (UGC) under Project No. C6003-22Y. C.N.M. would like to thank the UK company Solar Flow Ltd. (www.solar-flow.co.uk). For the purposes of Open Access, the authors have applied a CC BY public copyright license to any Author Accepted Manuscript version arising from this submission.

Appendix A. Model validation and sensitivity analysis

A.1. Applicability of the laminar flow model

This section assesses the applicability of the laminar-flow formulation adopted in Section 2.3 over the range of operating conditions considered in the steady-state analysis. The continuous air domain contains two geometrically distinct flow regions: (i) external flow over the upper surface of the glass convection cover and (ii) confined flow within the PV–water air gap. Because these regions differ in flow configuration and characteristic length scale, their Reynolds numbers are evaluated separately.

• External airflow over the convection cover

The external flow regime is assessed using the Reynolds number for flow over a flat plate:

$$Re_L = \frac{\rho u L}{\mu} \quad (\text{A.1})$$

where ρ and μ are the density and dynamic viscosity of air, respectively, u is the prescribed inlet velocity in the external air domain, and L is the length of the convection cover in the flow direction. For $L = 0.10$ m, $\rho = 1.2$ kg m^{−3}, and $\mu = 1.8 \times 10^{-5}$ Pa s at an ambient temperature of 25 °C, Re_L increases from 1.9×10^3 to 2.6×10^4 as u increases from 0.3 to 4.0 m s^{−1}. The maximum Reynolds number remains well below the commonly adopted critical value of $Re_{L,cr} \approx 5 \times 10^5$ for transition in external flow over a flat plate [34], supporting the use of the laminar flow formulation for the external airflow.

• Internal airflow within the PV–water air gap

The PV–water air gap is approximated as a rectangular channel with a width of W and a height of a . Its hydraulic diameter is calculated as

$$D_h = \frac{2Wa}{W + a} \quad (\text{A.2})$$

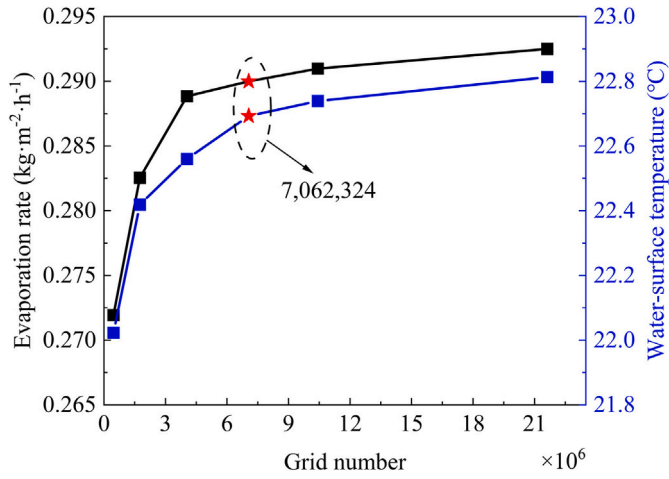


Fig. A.1. Grid-independence assessment of the PV-CLE model based on the area-averaged water-surface temperature and evaporation rate.

The corresponding Reynolds number in the gap is

$$Re_g = \frac{\rho u D_h}{\mu} \quad (A.3)$$

For the steady-state wind speed analysis with $a = 5$ mm, $W = 0.10$ m, and $T_{amb} = 25$ °C, the hydraulic diameter is $D_h = 9.5$ mm. Accordingly, Re_g increases from 1.8×10^2 to 2.4×10^3 as u increases from 0.3 to 4.0 m s⁻¹. For the steady-state air-gap-thickness analysis at $u = 0.3$ m s⁻¹ and $T_{amb} = 25$ °C, Re_g increases from 1.8×10^2 to 6.4×10^2 as a increases from 5 to 20 mm.

For flow between parallel plates, a critical Reynolds number of approximately 2.8×10^3 has been reported for the onset of the laminar to turbulent transition [35]. The maximum value obtained under the investigated steady-state conditions is $Re_g = 2.4 \times 10^3$, corresponding to $a = 5$ mm and $u = 4$ m s⁻¹. Although this value approaches the reported transition threshold, it remains below it. Accordingly, all steady-state cases considered in this study are modeled as laminar flow.

A.2. Grid-independence analysis

A grid-independence analysis was conducted to ensure numerical accuracy while maintaining a reasonable computational cost. Six mesh-resolution levels were examined, with the area-averaged water surface temperature and evaporation rate selected as the monitored quantities. As shown in Fig. A.1, the selected mesh contains 7,062,324 elements. For both monitored quantities, the relative differences between the selected mesh and the next finer mesh are less than 1%. The selected mesh was therefore adopted for all subsequent simulations.

A.3. Model validation

The integrated PV-CLE system comprises a PV component for electricity generation and a CLE unit for water-vapor production; therefore, it involves coupled solar-energy conversion, heat transfer, and evaporation. For STPV devices, spectral splitting governs the allocation of incident solar energy among electrical output, residual heat generation within the PV cells, and solar radiation transmitted to the evaporation side. The subsequent heat transfer and evaporation processes are governed by the same physical framework used for the opaque PV configuration. Accordingly, the spectral-splitting methodology is first benchmarked against published solar-energy-allocation results, after which the integrated PV-CLE model is validated directly against experimental measurements.

First, the spectral-splitting methodology is benchmarked against reported energy-allocation and electrical-conversion results for a

PV-thermal collector incorporating a semi-transparent PSC [38]. In that system, the PV layer functions as both an electricity generation component and a spectrally selective filter, partitioning the incident solar energy among electrical output, residual PV heat, and energy transmitted to and absorbed by the thermal absorber. As shown in Fig. A.2(a), the maximum relative error (RE) between the predicted and reported results is 1.8%. This agreement confirms the capability of the proposed spectral-splitting methodology to predict the allocation of incident solar energy.

Second, the integrated PV-CLE model is validated using measurements obtained from an indoor experimental platform developed in this study. As shown in Fig. A.2(b), the platform consists of a 13.5 cm × 16.5 cm polycrystalline-silicon PV panel positioned 30 mm above a thermally insulated water basin containing a 4-cm-deep water layer. An acrylic cover is installed above the PV panel to limit convective heat exchange with the surroundings; however, it does not enclose the PV-water air gap. The gap remains laterally open, allowing the generated vapor to be removed by ambient airflow.

During the experiments, the indoor air velocity fluctuates around 0.3 m s⁻¹; this representative value is therefore prescribed in the corresponding steady-state simulation. The experiments are conducted using pure water. Owing to the large illuminated area of the solar simulator, the local ambient conditions around the test platform correspond to an air temperature of 35 °C and a relative humidity of 25%. The electrical, thermal, and evaporation responses are monitored simultaneously under an irradiance of 1000 W m⁻² at the PV surface, with the electrical output measured at the maximum power point. The PV temperature is measured at the center of its rear surface, whereas the near-surface water temperature is measured at the center of the basin, 1 mm below the water surface. The corresponding simulated temperatures are extracted at the same locations. Measurements recorded after the system reached a steady state during the 4-hour experiments are used for comparison with the model predictions. The geometry, PV cell properties, boundary conditions, and operating conditions used in the simulation are specified to reproduce the experimental setup.

As shown in Fig. A.2(c), the absolute differences between the simulated and measured PV-cell and water temperatures are 0.6 and 1.2 °C, respectively. The relative errors in electrical efficiency and evaporation rate are 0.34% and 2.81%, respectively. The close agreement between the simulated and experimental results supports the predictive capability of the integrated PV-CLE numerical model under the tested operating conditions.

A.4. Boundary conditions

A.4.1. Specification of boundary conditions

The boundary conditions used in the coupled airflow, moisture transport, heat transfer, and surface-to-surface radiation models are summarized in Table A.1. The spatial locations of the principal boundaries are illustrated in Fig. 7.

A.4.2. Impact of simplified thermal boundary conditions

Two simplified thermal boundary conditions are adopted to avoid explicitly resolving the lateral insulation and the substantially larger surrounding-water reservoir. First, the lateral surfaces of the PV component and convection cover are treated as adiabatic to represent the insulated sides of the device. Second, the reservoir temperature is prescribed at the external surfaces of the floating insulation to represent thermal coupling with the surrounding bulk water. The adequacy of these simplifications is assessed using the PSC-CLE configuration under the baseline operating conditions. The resulting solar-to-electricity, solar-to-vapor, and overall equivalent efficiencies are summarized in Table A.2.

The lateral adiabatic approximation is assessed by replacing the adiabatic boundaries with a 5-mm-thick insulation layer having a thermal conductivity of 0.03 W m⁻¹ K⁻¹. A fully uninsulated case, in which the

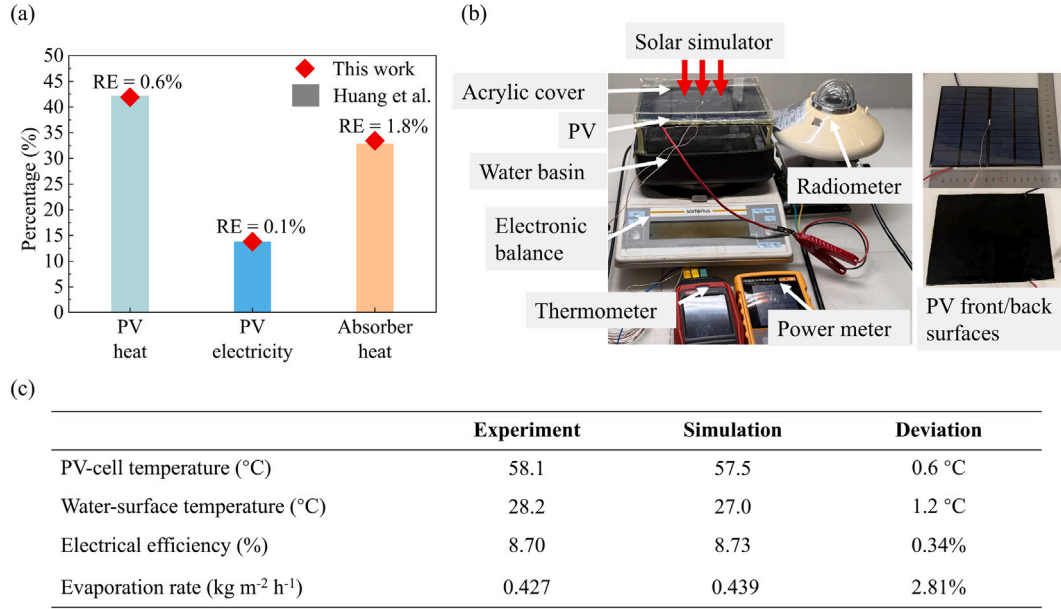


Fig. A.2. Model validation: (a) comparison of the predicted solar-energy allocation with published results [38], (b) experimental setup, and (c) comparison of the experimental and simulated performance of the integrated PV-CLE system. The deviations reported in panel (c) are absolute differences for the temperatures (°C) and relative errors for the electrical efficiency and evaporation rate (%).

Table A.1
Boundary conditions employed in the three-dimensional PV-CLE multiphysics model.

Physics	Location	Boundary condition
Airflow	Inlet of the external air domain	Uniform velocity inlet
Airflow	Remaining lateral and upper boundaries of the external air domain	Open boundary at ambient pressure
Airflow	PV cells, convection cover, and insulation surfaces exposed to air	No-slip wall
Moisture transport	Inlet of the external air domain	Ambient vapor concentration, $C_{v,amb} = \phi_{amb} C_{sat}(T_{amb})$
Moisture transport	Remaining lateral and upper boundaries of the external air domain	Open boundary
Moisture transport	Upper surface of the confined water layer	Wet surface condition at the local saturation concentration, $C_v = C_{sat}(T_w)$
Moisture transport	All non-evaporating solid and bottom boundaries	Impermeable boundary
Heat transfer	Inlet of the external air domain	Prescribed ambient temperature, $T = T_{amb}$
Heat transfer	Remaining lateral and upper boundaries of the external air domain	Open boundary
Heat transfer	Lateral surfaces of the convection cover and PV component	Adiabatic
Heat transfer	Upper surface of the convection cover	Surface-to-ambient radiative heat transfer with surface emittance ϵ_c and equivalent sky temperature T_{sky}
Heat transfer	Outer boundaries of the bulk-water domain	Prescribed ambient temperature, $T = T_{amb}$
Heat transfer	External insulation surfaces in contact with the surrounding bulk-water reservoir	Prescribed ambient temperature, $T = T_{amb}$
Heat transfer	PV cell surface	Boundary heat source representing residual PV heat, $Q_{h,PV}$
Heat transfer	Upper surface of the foam insulation positioned in water	Boundary heat source representing absorbed solar energy, $Q_{abs,ins}$
Surface-to-surface radiation	Rear surface of the PV cells	Diffuse gray radiating surface with emittance ϵ_{PV}
Surface-to-surface radiation	Upper surface of the confined water layer	Diffuse gray radiating surface with emittance ϵ_w

Note: The volumetric solar heat sources applied within the glass and water domains are specified in Section 2.3.3 and are therefore not included in this table.

lateral surfaces are directly exposed to the modeled ambient airflow, is also considered a limiting condition. The relatively small insulation thickness provides a conservative finite-insulation case because increasing the thickness would increase the lateral thermal resistance and cause the model to approach the adiabatic limit. Relative to the adiabatic model, the maximum relative differences in solar-to-electricity, solar-to-vapor, and overall equivalent efficiencies are 0.07%, 1.15%, and 0.58%, respectively. These small differences indicate that the adiabatic approximation adequately represents the insulated lateral surfaces for predicting system-level performance.

Thermal coupling between the floating insulation and the surrounding bulk water is represented by prescribing the reservoir temperature at the external surfaces of the insulation. This simplification is assessed using an extended model containing a surrounding-water domain measuring 300 mm in length, 300 mm in width, and 60 mm in depth. In the extended model, the prescribed reservoir temperature is applied at the outer boundary of the surrounding-water domain, while heat transfer between the floating insulation and the adjacent water is resolved explicitly. With the reservoir temperature set equal to the ambient temperature, the relative differences between the simplified

Table A.2

Predicted efficiencies obtained using alternative thermal boundary representations for the PSC–CLE system under the baseline operating conditions.

Boundary representation	η_e (%)	η_v (%)	η_o (%)
<i>Lateral thermal treatment</i>			
Adiabatic	14.05	41.85	78.81
5-mm-thick insulation, $k = 0.03 \text{ W m}^{-1} \text{ K}^{-1}$	14.05	41.37	78.35
Direct exposure to the modeled ambient airflow	14.06	41.85	78.84
<i>Representation of the surrounding bulk water</i>			
Reservoir temperature prescribed at the external surfaces of the floating insulation	14.05	41.85	78.81
Explicit lateral surrounding-water domain with the reservoir temperature prescribed at its outer boundary	14.05	41.86	78.82

Note: Both representations of the surrounding bulk water are evaluated with the reservoir temperature set equal to the ambient temperature.

and extended-domain models are 0%, 0.024%, and 0.01% for the solar-to-electricity, solar-to-vapor, and overall equivalent efficiencies, respectively. This close agreement supports the use of the simplified bulk-water boundary representation under the investigated conditions.

A.5. Sensitivity analysis of model input parameters

A.5.1. Analysis method

A deterministic, range-based, one-factor-at-a-time sensitivity analysis of input parameters is conducted for the PSC–CLE and c-Si–CLE systems, representing spectral-splitting and non-spectral-splitting configurations, respectively. The outer-surface emittance of the convection cover, equivalent-sky-temperature formulation, glass transmittance, PV rear-surface emittance, water-surface emittance, and reservoir temperature are varied individually under the reference operating conditions, while all other model inputs are held constant. The surface absorptance of the floating insulation is additionally examined for the PSC–CLE system. The solar-to-electricity, solar-to-vapor, and overall equivalent efficiencies are selected as the response quantities. The reference values and examined ranges are summarized in Table A.3.

For each response quantity Y , the relative deviation from the corresponding reference prediction is calculated as

$$\delta_{Y,i} = \frac{Y_i - Y_0}{Y_0} \quad (\text{A.4})$$

where Y_0 is the reference prediction and Y_i is the prediction obtained using the i th examined value or formulation. For each input, the maximum absolute relative deviation, $\max_i |\delta_{Y,i}|$, is used to characterize the magnitude of the model response over the examined range.

For each continuous input X , a dimensionless, range-normalized finite difference sensitivity coefficient is calculated as

$$S_{X,Y} = \frac{(Y_H - Y_L)/Y_0}{(X_H - X_L)/X_0} \quad (\text{A.5})$$

where X_0 is the reference input value, and the subscripts L and H denote the lowest and highest examined values, respectively. The magnitude of

$S_{X,Y}$ indicates the sensitivity of response Y to input X over the specified range, whereas its sign indicates the direction of the response. Because the equivalent-sky-temperature formulations constitute discrete model alternatives rather than a continuous numerical input, their effects are evaluated only using the relative deviations defined in Eq. (A.4).

A.5.2. Response of system efficiencies to input parameters

The maximum absolute relative deviations of the three performance metrics over the examined input ranges are presented in Fig. A.3. The model inputs are shown in the same order for both configurations to enable direct comparison.

For PSC–CLE, glass transmittance produces the largest variations in all three performance metrics, with maximum deviations of 4.07%, 3.58%, and 3.81% in the solar-to-electricity, solar-to-vapor, and overall equivalent efficiencies, respectively. For the vapor-related and overall responses, the floating insulation surface absorptance produces the second largest deviations over the examined ranges, reaching 2.0% and 1.06%, followed by the reservoir temperature, with corresponding deviations of 1.44% and 0.76%. For c-Si–CLE, glass transmittance likewise produces the largest variations in the solar-to-electricity, solar-to-vapor, and overall equivalent efficiencies, reaching 3.76%, 2.90%, and 3.47%, respectively.

Increasing the convection cover outer surface emittance from 0.04 to 0.20 slightly increases the solar-to-electricity efficiency while decreasing the solar-to-vapor and overall equivalent efficiencies. The maximum absolute relative deviations in these three efficiencies are 0.07%, 0.56%, and 0.26% for PSC–CLE, and 0.15%, 1.10%, and 0.27% for c-Si–CLE, respectively. The equivalent-sky-temperature formulation has a limited influence on both systems, with deviations not exceeding 0.073% for all three performance metrics.

A.5.3. Sensitivity coefficients

Because the examined inputs span different relative ranges, their maximum deviations alone do not provide a consistent basis for comparing relative sensitivities. Range-normalized sensitivity

Table A.3

Reference values and variations considered in the model-input sensitivity analysis.

Input	Reference value	Examined values	Basis of variation
Convection-cover outer-surface emittance, ϵ_c	0.04	0.04, 0.10, and 0.20	Prescribed increases from the reference value
Equivalent-sky-temperature formulation	Brunt	Brunt [36], Swinbank [54], and Idso [55]	Alternative empirical formulations
Glass transmittance, τ_g	0.96	0.94, 0.96, and 0.98	Prescribed absolute perturbation of ± 0.02
PV rear-surface emittance, ϵ_{PV}	0.94	0.92, 0.94, and 0.96	Prescribed absolute perturbation of ± 0.02
Water-surface emittance, ϵ_w	0.95	0.95, 0.96 [56], and 0.97 [57]	Reference value and literature-based alternatives
Floating-insulation surface absorptance, α_{ins}^a	0.99	0.95, 0.97, and 0.99	Prescribed decreases from the reference value
Reservoir temperature, $T_{reservoir}$	298.15 K	296.15 K, 298.15 K, and 300.15 K	2 K below and above the reference value

^aApplicable only to the PSC–CLE system because this surface is not part of the solar-energy absorption pathway in the c-Si–CLE system.

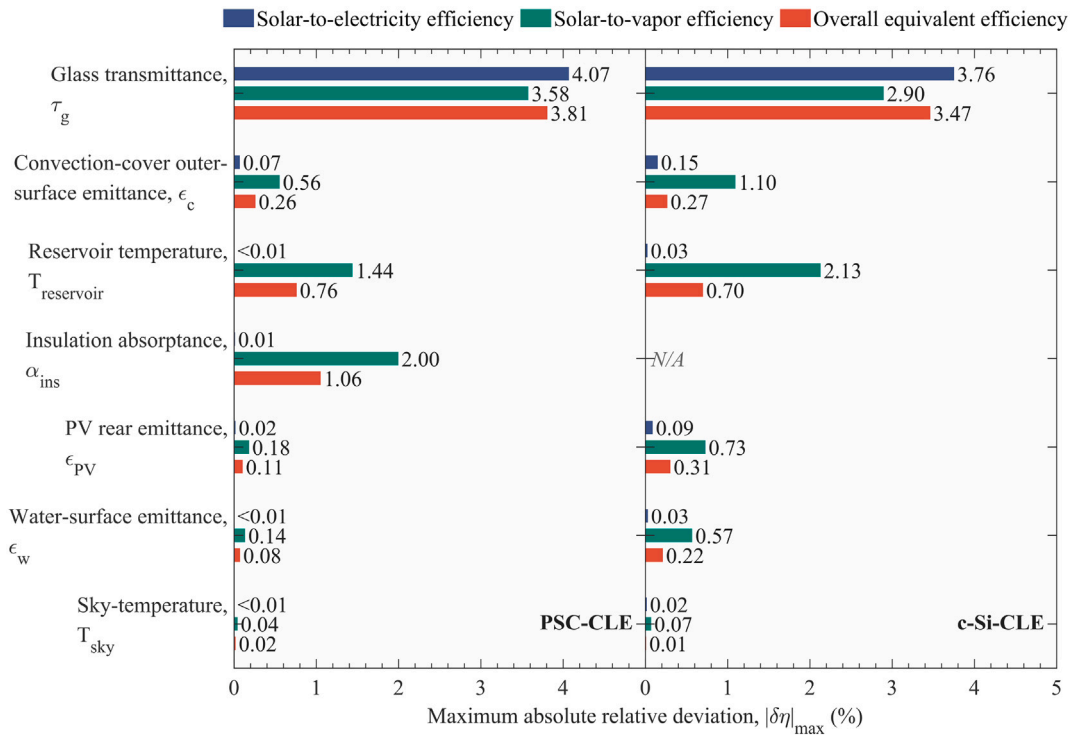


Fig. A.3. Maximum absolute relative deviations in the solar-to-electricity, solar-to-vapor, and overall equivalent efficiencies over the examined ranges of the model inputs for the PSC-CLE system (left) and the c-Si-CLE system (right). The floating-insulation surface absorptance is applicable only to the PSC-CLE system.

Table A.4

Range-normalized sensitivity coefficients of the predicted efficiencies with respect to the continuous model inputs.

Input	PSC-CLE			c-Si-CLE		
	S_{X,η_e}	S_{X,η_v}	S_{X,η_o}	S_{X,η_e}	S_{X,η_v}	S_{X,η_o}
Convection-cover outer-surface emittance	1.80×10^{-4}	-1.39×10^{-3}	-6.55×10^{-4}	3.83×10^{-4}	-2.74×10^{-3}	-6.73×10^{-4}
Glass transmittance	1.93	1.72	1.82	1.80	1.37	1.65
PV rear-surface emittance	0.006	0.059	0.034	0.019	0.172	0.071
Water-surface emittance	0.003	0.065	0.036	0.016	0.272	0.102
Floating-insulation surface absorptance	-0.003	0.495	0.261	N/A	N/A	N/A
Reservoir temperature	-0.01	2.14	1.13	-0.029	3.16	1.05

coefficients are therefore calculated for the continuous inputs and reported in Table A.4.

The normalized coefficients demonstrate that the relative sensitivity depends on both the PV configuration and the response quantity. Reservoir temperature produces the largest normalized response in solar-to-vapor efficiency, with sensitivity coefficients of 2.14 for PSC-CLE and 3.16 for c-Si-CLE. Glass transmittance produces the largest normalized responses in solar-to-electricity and overall equivalent efficiencies. The corresponding coefficients are 1.93 and 1.82 for PSC-CLE and 1.80 and 1.65 for c-Si-CLE, respectively. By contrast, the outer-surface emittance of the convection cover has little influence on the predicted efficiencies in either configuration, with coefficient magnitudes below 3×10^{-3} for all three response quantities. The differences between the rankings based on maximum deviations and those based on normalized sensitivity coefficients arise from the unequal relative ranges over which the inputs are varied.

Over the examined ranges, glass transmittance produces the largest absolute relative deviations in all three efficiencies for both configurations. The vapor-related predictions are also sensitive to reservoir temperature and, in the PSC-CLE system, the surface absorptance of the floating insulation. Variations in the emittances of the convection cover outer surface, PV rear surface, and water surface have comparatively minor effects. Similarly, the alternative equivalent-sky-temperature

formulations produce relative deviations below 0.073%. Collectively, these results indicate that the principal conclusions regarding the comparative performance of the PSC-CLE and c-Si-CLE systems are robust to the investigated variations in model inputs.

Appendix B. Transient performance under representative meteorological conditions

The daytime transient behavior of the PV-CLE systems is evaluated over a 9-h period from 08:30 to 17:30 using the time-dependent formulation of the coupled model. Hourly solar irradiance, ambient temperature, relative humidity, and wind speed are obtained from the Himawari Typical Meteorological Year dataset (TMY-2020) in the National Solar Radiation Database for Hong Kong (22.29°N, 114.18°E) [58]. A representative warm and humid day with high solar irradiance is selected, and the corresponding time-varying meteorological inputs are shown in Fig. B.1.

All computational domains are initialized at 29.0 °C, corresponding to the ambient temperature at 08:30. The meteorological inputs are held constant within each hourly interval and are updated at the beginning of each subsequent interval from 09:30 onward. Based on the gap Reynolds number criterion described in Appendix A.1, the low-Reynolds-number $k-\epsilon$ turbulence model is applied when the adopted transition Reynolds

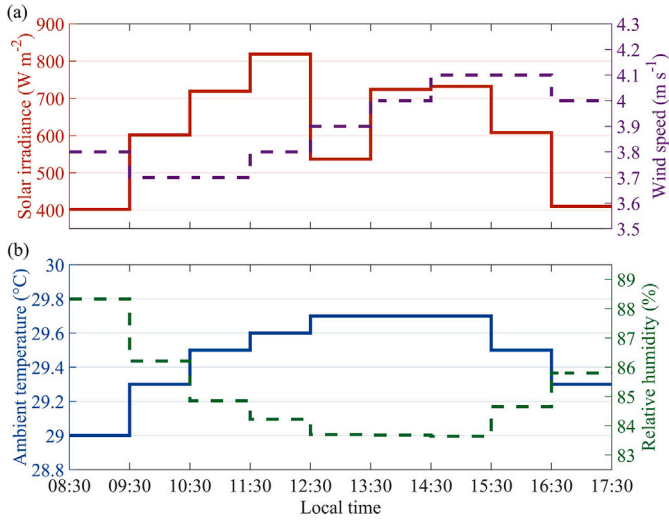


Fig. B.1. Hourly meteorological inputs used in the 9-h transient simulations: (a) solar irradiance and wind speed and (b) ambient temperature and relative humidity. Each value is held constant over the subsequent 1-h interval, with the conditions specified at 16:30 maintained until the end of the simulation at 17:30.

number is exceeded; all remaining cases are simulated using the laminar-flow model. The results are recorded at 10-min intervals.

B.1. Effect of air-gap thickness

The effect of air-gap thickness is first evaluated for the PSC-CLE system using thicknesses of 5, 10, 15, and 20 mm. As shown in Fig. B.2(a), the PV cell and water surface temperatures differ only slightly among

the four configurations. The solar-to-electricity efficiency is also nearly independent of the air-gap thickness, whereas the solar-to-vapor and overall equivalent efficiencies consistently decrease as the gap thickness increases (see Fig. B.2(b–d)). This trend is attributed to weaker thermal coupling between the PV cell and water surface at larger gaps, while the direct transmission of solar radiation to the evaporation region remains essentially unaffected. Consequently, the 5-mm configuration maintains the highest solar-to-vapor and overall equivalent efficiencies over the investigated range.

B.2. Comparisons of the four systems

The transient performance of the absorber-only CLE reference and the three PV-CLE systems is subsequently compared using the baseline air-gap thickness of 5 mm. As shown in Fig. B.3(a), the absorber-only reference maintains the highest absorber temperature, followed by the c-Si-CLE system, whereas the CdTe-CLE and PSC-CLE systems operate at substantially lower PV-cell temperatures. Their water surface temperatures, however, do not decrease in proportion to their PV cell temperatures because a portion of the incident solar spectrum is transmitted through the STPV layer and delivered directly to the evaporation region.

The corresponding efficiencies are shown in Fig. B.3(b)–(d). The CdTe-CLE system maintains the highest solar-to-vapor efficiency, whereas the c-Si-CLE system provides the highest solar-to-electricity efficiency. By combining substantial vapor production with electricity generation, the PSC-CLE system maintains the highest overall equivalent efficiency throughout the simulation period. The rapid changes following the hourly meteorological updates arise from the imposed stepwise boundary conditions and the subsequent thermal response of the systems. Despite these transient variations, all three PV-CLE systems maintain higher overall equivalent efficiencies than the absorber-only

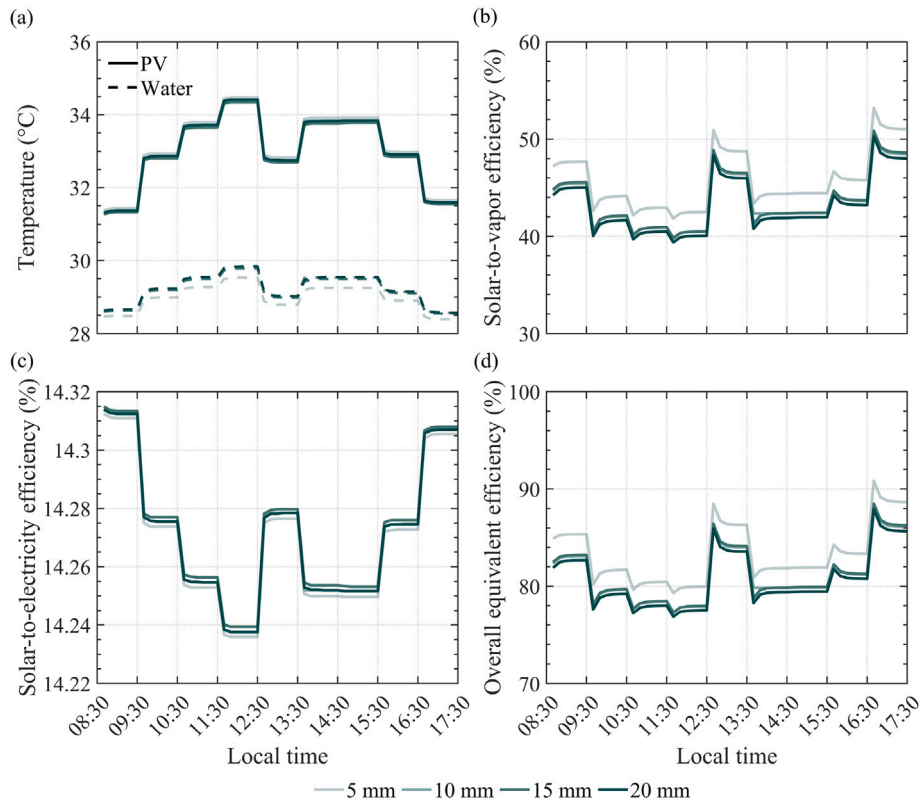


Fig. B.2. Transient performance of the PSC-CLE system with air-gap thicknesses of 5, 10, 15, and 20 mm under representative meteorological conditions from 08:30 to 17:30: (a) PV cell and water surface temperatures, (b) solar-to-vapor efficiency, (c) solar-to-electricity efficiency, and (d) overall equivalent efficiency.

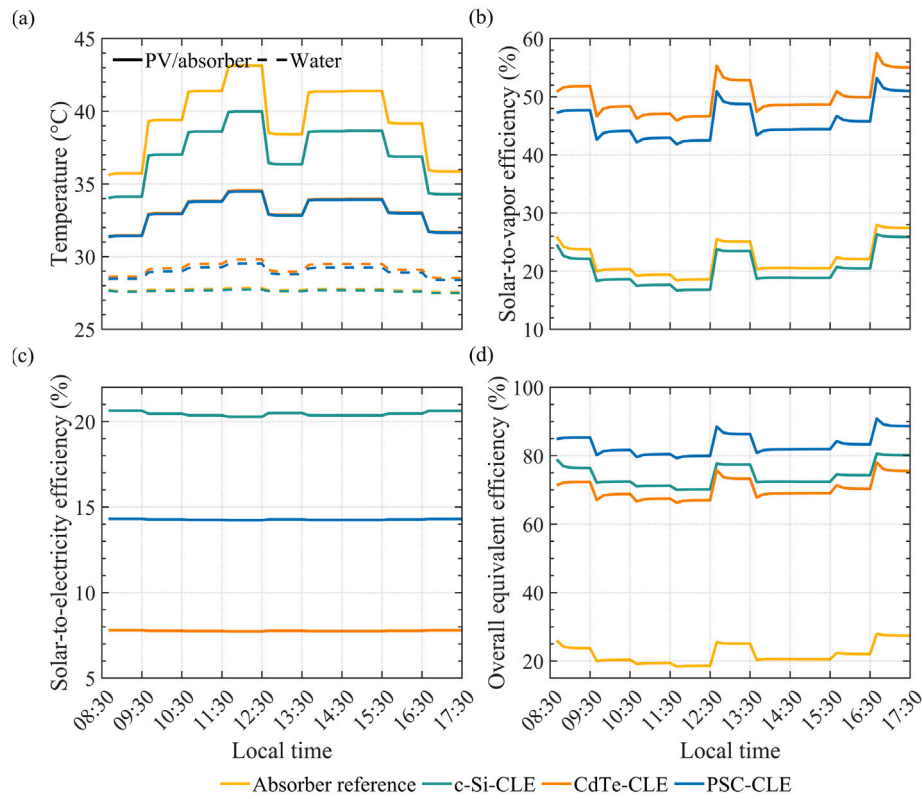


Fig. B.3. Transient performance of the four investigated systems under representative meteorological conditions from 08:30 to 17:30: (a) PV cell/absorber and water surface temperatures, (b) solar-to-vapor efficiency, (c) solar-to-electricity efficiency, and (d) overall equivalent efficiency.

reference, and their relative performance characteristics remain unchanged throughout the representative daytime period.

The time-dependent energy flows shown in Fig. B.4 further explain these performance differences. For each system, the upper and lower panels present the energy flows on the PV cell/absorber and water sides, respectively. The absorber-only reference and c-Si-CLE systems exhibit greater convective losses from the rear surface than the two STPV systems. By contrast, the CdTe-CLE and PSC-CLE systems additionally

deliver transmitted solar energy directly to the evaporation region. The CdTe-CLE system directs a larger fraction of the available energy toward evaporation, whereas the PSC-CLE system combines substantial water-side energy input with greater electricity generation. Although the magnitudes of the individual energy flows vary with the meteorological conditions, the characteristic energy transfer pathways of the four systems are retained throughout the simulated daytime period.

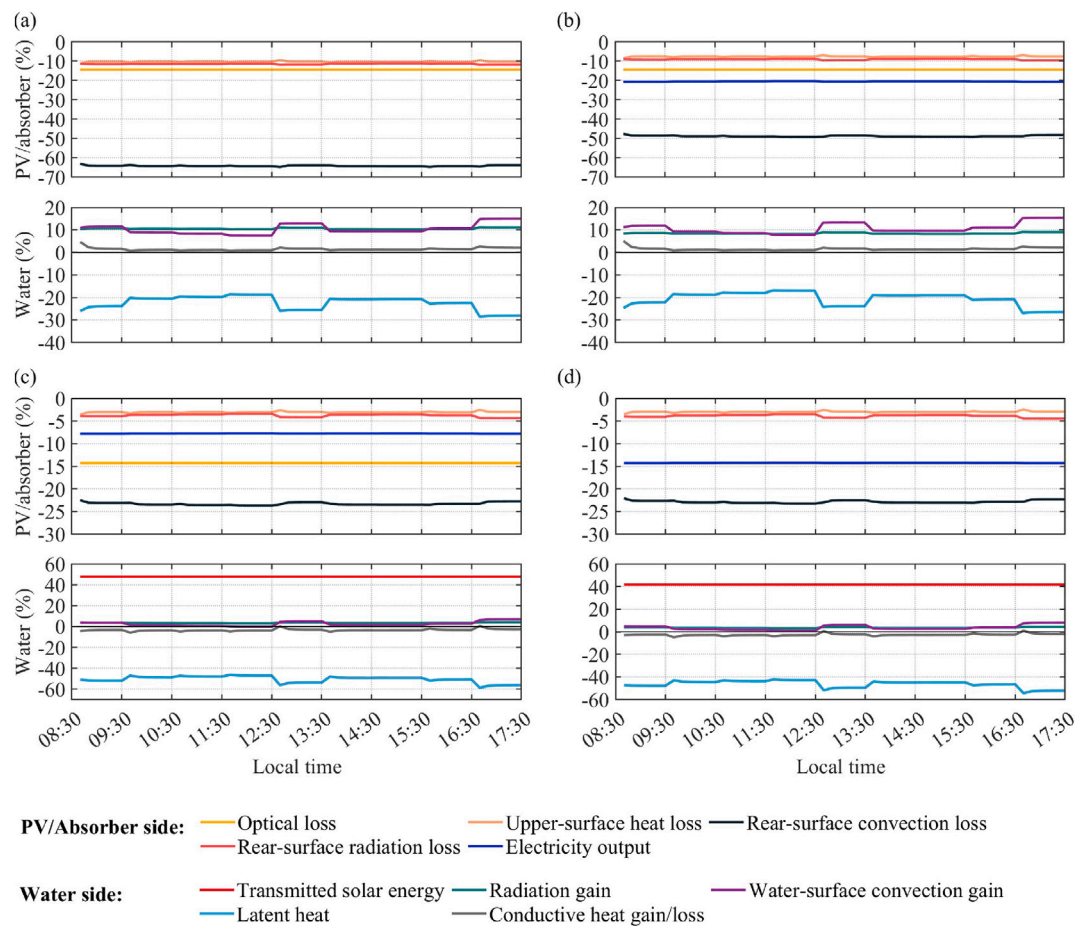


Fig. B.4. Time-dependent energy flow components of (a) the absorber-only CLE reference, (b) c-Si-CLE, (c) CdTe-CLE, and (d) PSC-CLE under representative meteorological conditions. For each system, the upper and lower panels show the PV cell/absorber-side and water-side energy flows, respectively. Negative values denote energy losses from or outputs of the corresponding domain, whereas positive values denote energy inputs.

Data availability

The data in this study are available upon request.

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