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Water-Level-Regulated Ridge-Structured Evaporator for Salt-Resistant Solar Desalination with Radiative Heat Recovery

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Supporting Information

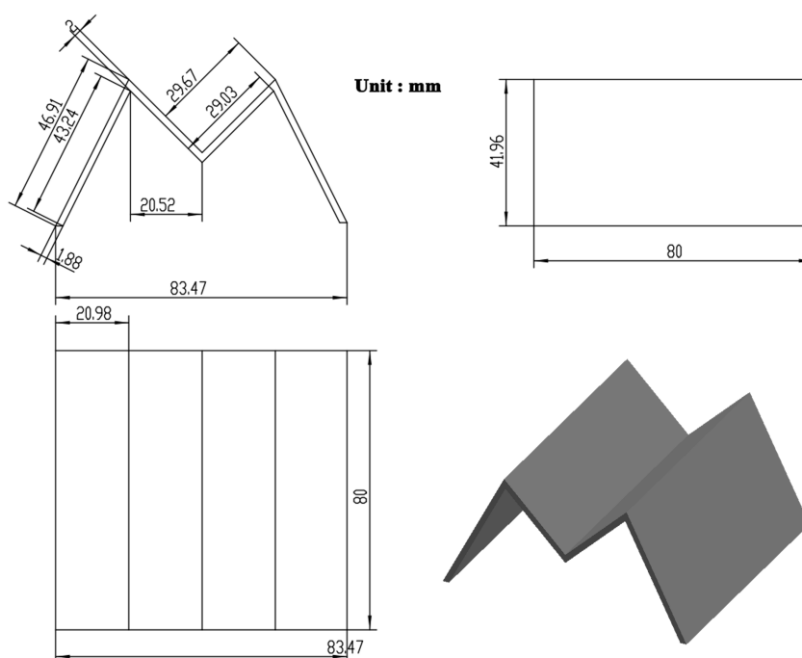


Figure S1: Detailed dimensionnal parameters of the double-peak ridge structured evaporator.

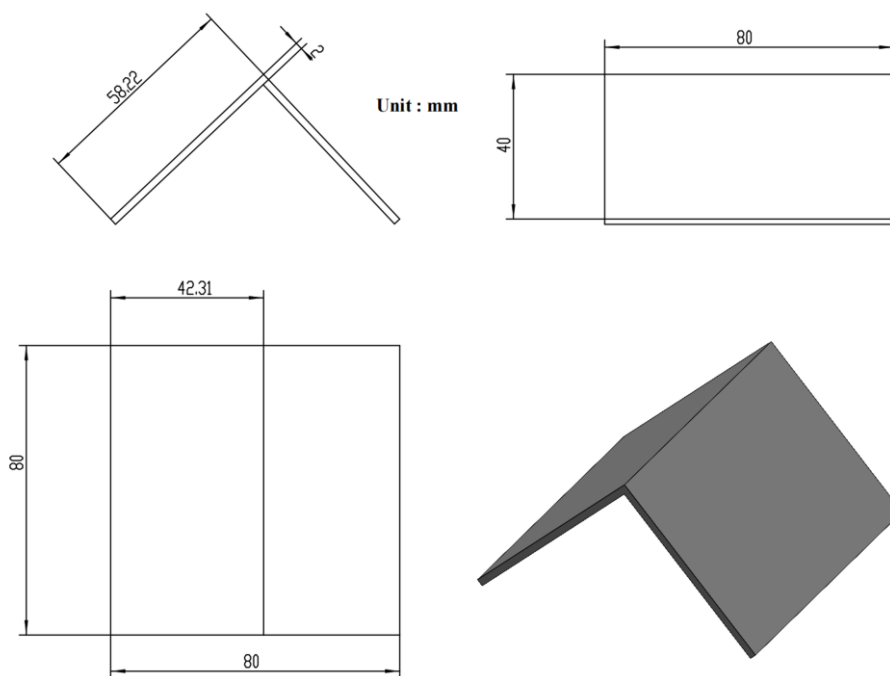


Figure S2: Detailed dimensional parameters of the single-peak ridge structured evaporator

Note S1 Raman Characterization of water Evaporation

To verify the ability of the RSE to regulate water molecular behavior, Raman spectra of pure water and RSE were measured and analyzed. Specifically, the prepared evaporator was cut into a flat block with dimensions of 2×2 mm and a thickness of 2 mm, which was then placed on the sample stage. A small amount of water was subsequently dropped onto the sample to allow it to swell sufficiently prior to testing. A 633 nm excitation laser was focused on the sample surface, and Raman spectra were recorded over the wavenumber range of $2700\text{--}4000\text{ cm}^{-1}$. The obtained spectra were fitted using Gaussian functions, and the results are presented as follows.

Table S1: The ratio of FW and IW in pure water and water in prepared sample.

Sample	FW	IW	IW : FW
Pure water	2.55%, 64.01%	29.83%, 3.61%	0.502
Water in RSE	13.12%, 3.80%	78.23%, 4.85%	4.910

Note S2 Evaporation process under dark conditions

Dark evaporation experiments were conducted at a temperature of $25 \pm 2^\circ\text{C}$, and a humidity of $52 \pm 2\%$ to determine the evaporation enthalpy. The evaporator and pure water were placed in this environment for 12 h, and all experiments were performed in triplicate. Under dark conditions, the evaporation rates of pure water and RSE were 0.19 and $0.30\text{ kg m}^{-2}\text{ h}^{-1}$, respectively.

The following assumption was made: The energy input to both the bulk water and the evaporator was identical. Based on the measured mass of evaporated water, the evaporation enthalpy was calculated using the following equation [1].

$$m_{water,25^{\circ}C}h_{e,water,25^{\circ}C} = m_{eva,25^{\circ}C}h_{e,eva,25^{\circ}C} \quad (1)$$

where $m_{water,25^{\circ}C}$ and $m_{eva,25^{\circ}C}$ were measured evaporation rate of pure water and evaporator under dark conditions ($\text{kg m}^{-2} \text{h}^{-1}$); $h_{e,water,25^{\circ}C}$ and $h_{e,eva,25^{\circ}C}$ were the evaporation enthalpy of pure water and evaporators under dark conditions, respectively.

Table S2: Enthalpy of water evaporation (J g^{-1}) for pure water and RSE, obtained from three independent measurements.

Enthalpy (J g^{-1})	1	2	3	Average value	Equivalent evaporation enthalpy
Pure water	2273	2277	2274	2275 ± 2.1	2450
Water in RSE	1581	1609	1586	1592 ± 14.9	1552

Note S3 Photothermal Conversion Efficiency

The photothermal conversion efficiency (η) of the AMBG was calculated by the following formulation.

$$\eta_{evap} = \frac{m_{net}h_{LV}}{q_{solar}} = \frac{(m_{light}-m_{dark})h_{LV}}{C_{opt}P} \quad (2)$$

Where m_{light} and m_{dark} ($\text{kg m}^{-2} \text{h}^{-1}$) are the mass fluxes measured under illumination and in the dark, respectively, $m_{net} = m_{light} - m_{dark}$ is the net solar-driven evaporation rate, h_{LV} is the enthalpy change of liquid to vapor (sensible heat and evaporation enthalpy) (MJ kg^{-1}) obtained by evaporation process in dark (Note S2); C_{opt} is the optical concentration on the vaporization interface ($C_{opt} = 1$ in this work); P is the solar power intensity of 1 sun (1 kW m^{-2}).

In this framework, convective and radiative heat losses are treated in two ways:

(1) Background convective/radiative losses in the setup

The dark mass flux m_{dark} is measured with the same device and water level but without illumination. This term represents water loss caused by natural convection, ambient evaporation, and radiative exchange between the water surface and the surroundings in the absence of photothermal heating. By subtracting m_{dark} from the illuminated mass flux, these background convective/radiative losses are quantitatively removed from the numerator, so that m_{net} reflects only the evaporation driven by absorbed solar energy.

(2) Residual optical and thermal losses

The denominator $q_{solar} = C_{opt}P$ corresponds to the total incident solar power on the projected area, without correction for reflection, transmission, or re-radiation. Therefore, any optical losses (reflection, scattering) and residual convective/radiative heat dissipation from the evaporator to the ambient are implicitly included in the input energy term. In other words, the reported efficiency is an effective solar-to-vapor efficiency based on the net evaporation enthalpy in the numerator and the total incident solar power in the denominator. This treatment makes the reported value conservative, as all unavoidable loss channels are counted against the input.

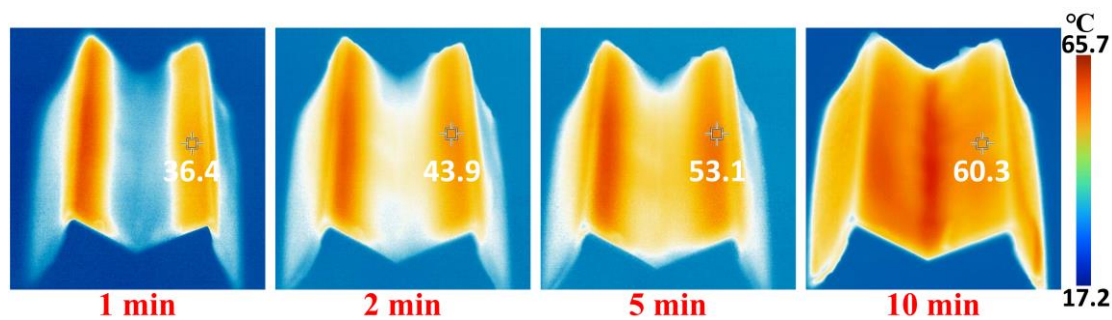


Figure S3 Infrared thermal images of RSE under 1 kW m⁻² irradiation in dry conditions.

Note S4 COMSOL Simulation and Thermal Field Analysis

To examine the internal temperature distribution within the interfacial Structure, a detailed heat-transfer model was constructed using COMSOL Multiphysics to accurately simulate the geometry and key physical characteristics of RSE evaporators. The model incorporated the actual dimensions of the evaporator and accounted for the thermophysical properties of each component, including thermal conductivity, density, and specific heat capacity. Appropriate initial and boundary conditions, including a prescribed incident solar flux of 1 kW m⁻² and natural convection heat transfer from the surrounding air, were implemented to replicated practical operating conditions, alongside consideration of interfacial water evaporation. This comprehensive Multiphysics framework enabled the detailed analysis of transient heat transport behavior and spatial temperature evolution within RSE evaporators.

Table S3: Sample Property Values of RSE evaporators used finite element simulations.

Sample	ρ (kg m ⁻³)	λ (W m ⁻¹ K ⁻¹)
3D printing substate	1240	0.17
CNTs@CF	784	3.1

Note S5 COMSOL Simulation of Airflow Transport around the RSE

To investigate the airflow regulation behavior of the ridge-structured evaporator (RSE), numerical simulations were performed using COMSOL Multiphysics. A three-dimensional RSE model was constructed according to its actual geometric dimensions, including the inclined ridge surfaces, ridge peaks, and central valley. The RSE model was placed within a rectangular air domain to reproduce the surrounding airflow environment. Air was defined as an incompressible Newtonian fluid, while all RSE surfaces were treated as no-slip walls. The computational mesh was locally refined near the inclined surfaces, ridge peaks, and central valley to improve the accuracy of the airflow calculation.

Two incoming-flow directions were considered. For airflow parallel to the ridge direction, a prescribed velocity inlet was applied to one side of the air domain along the longitudinal ridge channels, and the opposite boundary was defined as a pressure outlet. For airflow perpendicular to the ridge direction, the inlet and outlet boundaries were rotated accordingly so that the incoming airflow directly interacted with the inclined ridge surfaces. The remaining external boundaries were defined as open or slip boundaries to minimize wall-confinement effects.

The stationary laminar-flow module was used to calculate the airflow velocity field. Airflow vectors and velocity contours were extracted from representative cross-sectional planes and visualized from different viewing angles to evaluate airflow transport along the ridge channels, flow deflection by the inclined surfaces, and vapor-removal pathways above the RSE.

Note S6 COMSOL Simulation of Water Transport in the RSE

To investigate the water-supply behavior of the ridge-structured evaporator under low-water-level conditions, a time-dependent numerical simulation was conducted using COMSOL Multiphysics. A three-dimensional RSE model was constructed according to its actual geometric dimensions, including the inclined ridge surfaces, ridge peaks, and central valley. The evaporator was treated as a homogeneous porous medium, and its porosity, permeability, and capillary-pressure-related parameters were assigned according to the material properties. Gravity was included in the simulation to account for its influence on upward water transport.

The regions at both lower sides of the RSE that were in contact with bulk water were defined as saturated water-supply boundaries to reproduce the low-water-level operating condition. The remaining exposed surfaces were assigned no-liquid-flux boundaries, allowing the capillary-driven wetting process to be evaluated independently. The initial water saturation of the RSE was set to a low value to represent the initially dry state.

The time-dependent Richards' Equation interface was used to simulate unsaturated water transport within the porous RSE. The computational mesh was locally refined near the water-contact regions, ridge peaks, inclined surfaces, and central valley to improve the accuracy of the wetting-front calculation. Water-saturation contours and flow-velocity vectors were extracted at different times to visualize the upward and inward transport of water from both sides toward the ridge peaks and central region.

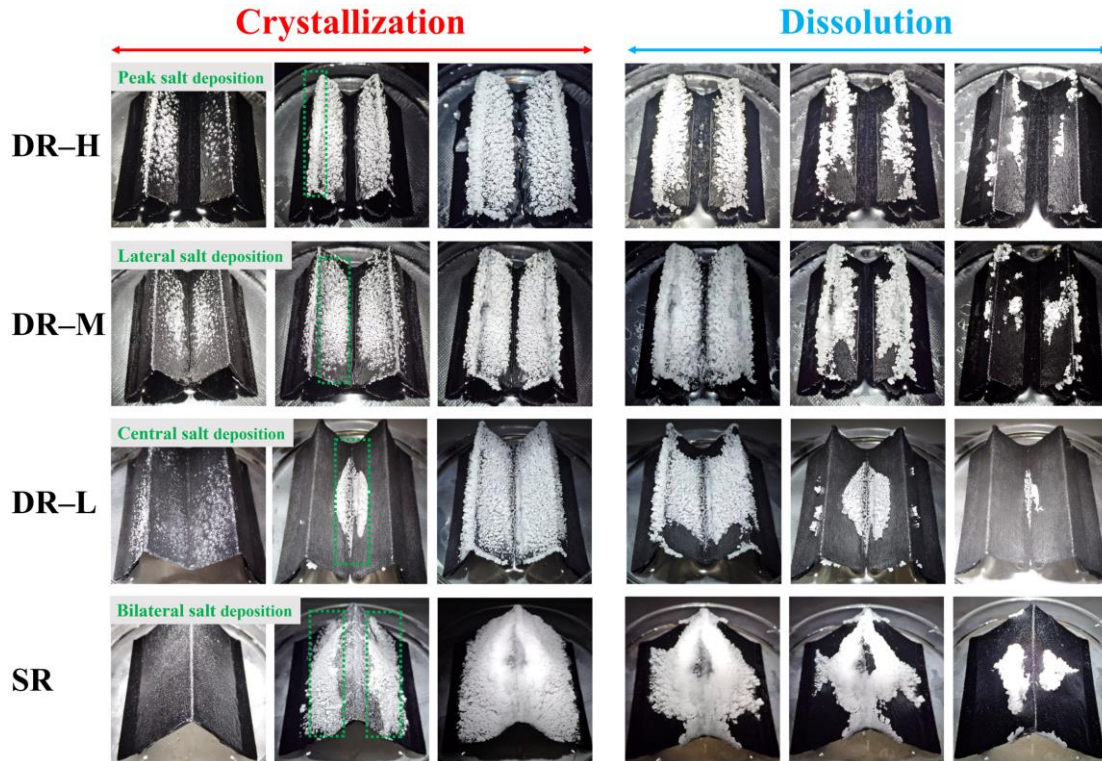


Figure S4: Salt crystallization and dissolution behaviors of DR-H, DR-M, DR-L, and SR in 20 wt% NaCl solution.

Note S7 Freshwater collection performance of the RSE arrays

To further evaluate the practical freshwater-production capability of the RSE system, the freshwater collection performance of the 9-unit and 15-unit arrays was evaluated using the integrated condensation and collection device. During the 10 h outdoor collection test, the water vapor generated from the RSE arrays was condensed on the inner condensation surfaces and subsequently collected in the freshwater reservoir.

The freshwater collection rate was calculated according to

$$R_{col} = \frac{m_{col}}{t} \quad (3)$$

Where R_{col} is the average freshwater collection rate (kg h^{-1}), m_{col} is the collected freshwater mass (kg), and t is the collection time (h).

The freshwater collection efficiency was calculated as

$$\eta_{col} = \frac{m_{col}}{m_{evap}} \times 100\% \quad (4)$$

Where η_{col} is the freshwater collection efficiency, m_{col} is the collected freshwater mass (kg), and m_{evap} is the corresponding evaporator-water mass during the same collection period.

During the 10 h collection test, the 9-unit and 15-unit RSE arrays collected 1.595 and 2.624 kg of freshwater, corresponding to average freshwater collection rates of 0.1595 and 0.2624 kg h^{-1} , respectively. The corresponding evaporated-water masses were approximately 1.762 and 2.868 kg, resulting in freshwater collection efficiencies of approximately 90.5% and 91.5%, respectively. These results indicate that most of the generated water vapor can be recovered by the condensation system, while the remaining loss is mainly associated with incomplete condensation and vapor escape from the collection device.

Table S4 Freshwater collection performance of the 9-unit and 15-unit RSE arrays during a 10 h collection test.

RSE array	Evaporated water in 10 h (kg)	Collected freshwater in 10 h (kg)	Average evaporation rate (kg h^{-1})	Average freshwater collection rate (kg h^{-1})	Freshwater collection efficiency (%)
9-unit	1.762	1.595	0.1762	0.1595	90.5
15-unit	2.868	2.624	0.2868	0.2624	91.5

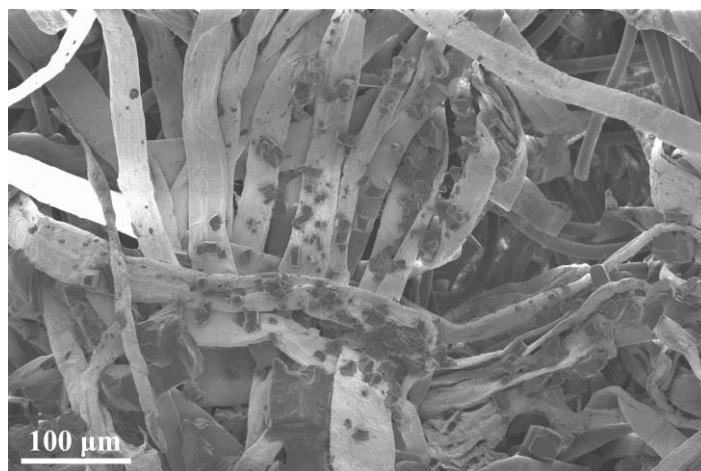


FIGURE S5 SEM image of salt deposition on the RSE surface after seawater evaporation.

Note S8 Cyclic Crystallization–Dissolution Stability Test

To further evaluate the reproducibility and long-term stability of the water-level-regulated salt-management strategy, repeated salt crystallization–dissolution cycling experiments were performed using the RSE in a 20 wt% NaCl solution under one-sun irradiation. Each cycle consisted of two successive stages, namely low-water-level salt crystallization and increased-water-level salt dissolution.

During the crystallization stage, the RSE was operated under the low-water-level condition, allowing salt to preferentially crystallize and accumulate in the central valley region during continuous evaporation. After obvious salt accumulation was observed, the water level was increased to shorten the water-transport pathway and enhance water replenishment to the crystallization region. The accumulated salt was then allowed to redissolve completely. After the dissolution process, the water level was returned to the original low-water-level condition to initiate the next crystallization cycle. This crystallization–dissolution procedure was consecutively repeated for 14 cycles.

The evaporation rate during each crystallization cycle was calculated according to

$$J = \frac{\Delta m}{A \Delta t} \quad (5)$$

Where J is the the evaporation rate ($\text{kg m}^{-2} \text{h}^{-1}$), Δm is the mass loss of the solution during the evaporation period (kg), A is the effective evaporation area of the RSE (m^2), and Δt is the evaporation time (h).

To quantitatively evaluate the regeneration capability of the RSE after salt accumulation, the salt dissolution efficiency was calculated as

$$\eta_d = \frac{m_{acc} - m_{res}}{m_{acc}} \times 100\% \quad (6)$$

Where η_d is the salt dissolution efficiency, m_{acc} is the mass of salt accumulated on the RSE before increasing the water level, and m_{res} is the mass of residual salt remaining on the RSE after the dissolution process.

As shown in Figure S6, the evaporation rate exhibited only a gradual decrease over the 14 consecutive crystallization–dissolution cycles. The evaporation rate decreased from $1.28 \text{ kg m}^{-2} \text{h}^{-1}$ in the first cycle to $1.15 \text{ kg m}^{-2} \text{h}^{-1}$ in the 14th cycle, corresponding to an evaporation-rate retention of approximately 89.8%. Specifically, the evaporation rates for cycles 1–14 were 1.28, 1.27, 1.26, 1.24, 1.23, 1.22, 1.21, 1.20, 1.20, 1.18, 1.17, 1.17, 1.16, and $1.15 \text{ kg m}^{-2} \text{h}^{-1}$, respectively. More importantly, the salt dissolution efficiency remained above 99% during all 14 cycles, indicating that the accumulated salt could be effectively removed after repeated water-level switching. The consistently high dissolution efficiency demonstrates that the water-level-regulated process retains its ability to regenerate the salt-covered region even after repeated crystallization and dissolution. Although a moderate decrease in evaporation rate was observed with increasing cycle number, no abrupt performance deterioration occurred during the 14-cycle test. Meanwhile, the consistently high salt dissolution efficiency indicates that the gradual change in evaporation performance was not caused by a progressive loss of the salt-removal capability. Overall, these results demonstrate that the RSE can repeatedly undergo low-water-level salt crystallization and increased-water-level salt dissolution while maintaining effective interface regeneration and relatively stable evaporation performance.

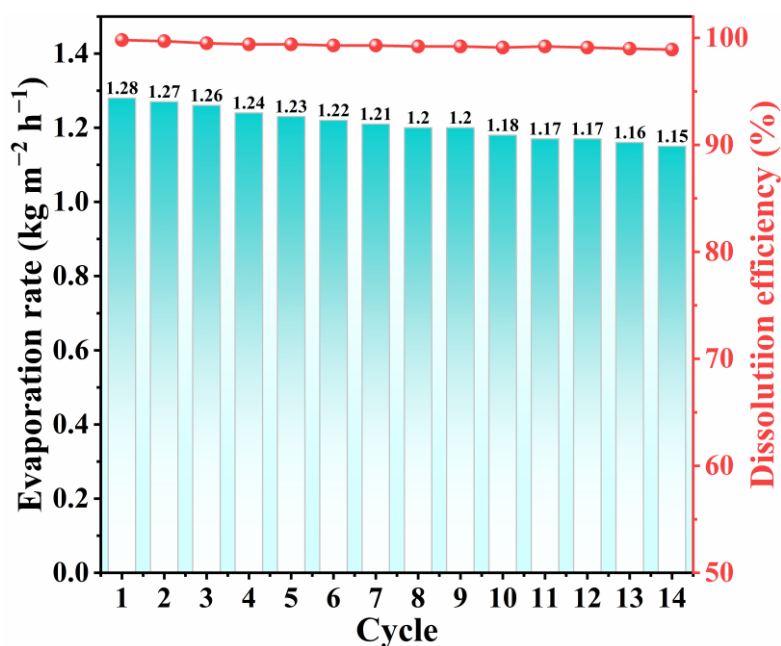


FIGURE S6: Evaporation rate and salt dissolution efficiency of the RSE over 14 consecutive low-water-level crystallization and increased-water-level dissolution cycles.

Table S5: Evaporation performance of the 9- and 15-unit RSE matrices during continuous operation in pure water and brine.

Day	Water Mass Change (kg)			
	Pure Water		Brine	
	9 matrices	15 matrices	9 matrices	15 matrices
1	1.82	3.19	1.7	2.93
2	0.42	0.74	0.39	0.67
3	1.66	2.91	1.54	2.65
4	0.92	1.62	0.85	1.47
5	1.75	3.07	1.63	2.8
6	1.84	3.23	1.72	2.97
7	0.4	0.7	0.37	0.64
8	1.63	2.86	1.51	2.6
9	0.88	1.54	0.81	1.4
10	1.78	3.12	1.66	2.85
11	0.44	0.77	0.4	0.69
12	1.68	2.95	1.56	2.69
13	1.73	3.02	1.6	2.76
14	0.95	1.67	0.88	1.52
15	0.39	0.68	0.36	0.62
16	1.8	3.16	1.68	2.9
17	1.65	2.89	1.53	2.63
18	0.41	0.72	0.38	0.65
19	0.9	1.58	0.81	1.44
20	1.76	3.09	1.64	2.82
21	1.82	3.2	1.7	2.94
22	0.43	0.75	0.39	0.68
23	1.67	2.93	1.55	2.67
24	0.93	1.64	0.86	1.49
25	1.79	3.14	1.67	2.88
26	1.71	3	1.59	2.74
27	0.39	0.69	0.36	0.63
28	1.62	2.84	1.5	2.58

Note S9 Economic Analysis and Preliminary LCOW Projection

To provide a more transparent assessment of the economic implications of scaling up the ridge-structured evaporator (RSE), a preliminary lifecycle cost analysis was conducted for nominal installation areas of 20, 50, and 100 m². The analysis was based on the experimentally measured freshwater production of the 9-unit and 15-unit arrays and the current laboratory-scale material and component costs. The purpose of this analysis is to provide a transparent cost projection under explicitly defined assumptions rather than a complete industrial techno-economic assessment.

The economic boundary includes the RSE units, CF substrate, carbon nanotubes (CNTs), and condensation device. The current model does not separately include industrial manufacturing labor, tooling, land, financing, feed-water pretreatment, brine disposal, or other balance-of-plant costs because reliable pilot-scale parameters for these items are not yet available. Operation and maintenance costs were assumed to be negligible in the base-case calculation. Therefore, the resulting cost should be interpreted as a preliminary economic projection under the specified assumptions.

Note S9.1 Economic assumptions and system boundary

Three nominal installation areas of 20, 50, and 100 m² were considered, corresponding to 2500, 6300, and 12,300 RSE units, respectively. The effective evaporation surface area of one RSE unit was approximately 120 cm². Because the RSE possesses a three-dimensional ridge geometry, the nominal installation area and the summed effective evaporation surface area were treated separately and were not considered interchangeable in the economic model.

The adopted cost and operating parameters are summarized in Table S7. The material cost of one RSE unit was estimated as 0.50 USD. The CF substrate cost was 0.30 USD m⁻². The CNT price was 450 USD per 100 g, corresponding to 4.50 USD g⁻¹, and approximately 1 g of CNTs was used to prepare 20 RSE units. The condensation device cost was estimated as 82.5 USD m⁻². The RSE-related replaceable components were assumed to be replaced every 0.5 year, whereas the condensation device was treated as a fixed component over the 20-year calculation period.

Table S6: Assumptions and parameters adopted for the preliminary economic analysis of the RSE system.

Parameter	Symbol	Adopted Value	Treatment in the model
Nominal installation area	A	20, 50, 100 m ²	Scale-up scenarios
Number of RSE units	N	2500, 6300, 12300	Corresponding to the three nominal scales
Effective evaporation area per RSE	a _{RSE}	120 cm ²	Three-dimensional evaporation surface
RSE unit material cost	C _{unit}	0.50 USD unit ⁻¹	Replaceable component
CF substrate cost	C _{CF}	0.30 USD unit ⁻¹	Replaceable component
CNT cost	C _{CNT}	4.50 USD unit ⁻¹	Replaceable component
CNT consumption	/	1 g per 20 RSE units	Used to calculate CNT cost
Condensation device cost	C _{con}	82.50 USD m ⁻²	Fixed component
Water collection duration	/	10 h day ⁻¹	Basis of experimental productivity
Operating days	D	365 days year ⁻¹	Base-case assumption
Replacement interval of RSE components	L _{RSE}	0.5 year	Base-case assumption

Economic evaluation period	T	20 years	Lifecycle projection
Operation and maintenance cost	$C_{O\&M}$	0 USD	Neglected in the base-case projection
Condensation efficiency	/	Not independently assumed	Experimental collected-water yield was used directly
Discount rate	i	0 in the present preliminary projection	No project-financing scenario was assigned
Industrial manufacturing and assembly cost	/	Not separately included	Requires pilot-scale manufacturing data

Note S9.2 Freshwater production basis

To avoid assuming complete conversion of evaporated water into collected freshwater, the economic analysis was based on the experimentally measured freshwater collection rather than the evaporation mass loss. Under 10 h of illumination, the 9-unit and 15-unit arrays produced 1.595 and 2.624 L of freshwater, respectively. The corresponding unit-normalized freshwater production values were calculated as

$$V_{unit,9} = 1.595/9 = 0.17722 \text{ L unit}^{-1} \text{ day}^{-1} \quad (7)$$

and

$$V_{unit,15} = 2.624/15 = 0.17493 \text{ L unit}^{-1} \text{ day}^{-1} \quad (8)$$

The average freshwater production adopted for one RSE unit was therefore

$$V_{unit} = (V_{unit,9} + V_{unit,15})/2 = 0.17608 \text{ L unit}^{-1} \text{ day}^{-1} \quad (9)$$

Because the economic calculation uses experimentally collected freshwater rather than evaporated water, condensation losses are already incorporated into the adopted productivity. Thus, no additional assumption of 100% condensation efficiency was introduced.

For a system containing N_{RSE} units, the daily freshwater production was calculated according to

$$V_{daily} = N \times V_{unit}/1000 \quad (10)$$

where the factor of 1000 converts liters to cubic meters. The annual freshwater production was calculated as

$$V_{annual} = V_{daily} \times D \quad (11)$$

and the cumulative freshwater production after an operating period of t years was determined from

$$V_{total} = V_{annual} \times t \quad (12)$$

Note S9.3 Material and component cost calculation

The costs of the RSE units, CF substrate, CNTs, and condensation device were calculated separately. The cost of the RSE units was determined from

$$C_{RSE} = N \times c_{unit} \quad (13)$$

The CF substrate cost was calculated as

$$C_{CF} = A \times c_{CF} \quad (14)$$

According to the adopted preparation consumption of 1 g CNTs for every 20 RSE units, the required CNT mass and corresponding cost were calculated as

$$m_{CNT} = N/20 \quad (15)$$

And

$$C_{CNT} = m_{CNT} \times c_{CNT} \quad (16)$$

The condensation device cost was calculated according to

$$C_{con} = A \times c_{con} \quad (17)$$

The initial system cost was then obtained from

$$C_{initial} = C_{RSE} + C_{CF} + C_{CNT} + C_{con} \quad (18)$$

For example, for the nominal 20 m² system,

$$C_{RSE} = 2500 \times 0.50 = 1250.00 \text{ USD}$$

$$C_{CF} = 20 \times 0.30 = 6.00 \text{ USD}$$

$$C_{CNT} = (2500/20) \times 4.50 = 562.50 \text{ USD}$$

$$C_{con} = 20 \times 82.5 = 1650.00 \text{ USD}$$

Therefore,

$$C_{initial} = 1250.00 + 6.00 + 562.50 + 1650.00 = 3468.50 \text{ USD}$$

The corresponding initial costs of the 50 and 100 m² systems were 8707.50 and 17,197.50 USD, respectively.

Note S9.4 Component replacement and lifecycle system cost

The condensation device was treated as a fixed component during the 20-year calculation period, whereas the RSE units, CF substrate, and CNTs were treated as replaceable components. The cost of one replaceable set was defined as

$$C_{rep} = C_{RSE} + C_{CF} + C_{CNT} \quad (19)$$

With an RSE replacement interval of 0.5 year, the total number of RSE sets required over an operating period t , including the initial set, was calculated as

$$n_{set(t)} = \text{ceil}(t/0.5) \quad (20)$$

The cumulative lifecycle cost was then calculated as

$$C_{total(t)} = C_{con} + n_{set(t)} \times C_{rep} \quad (21)$$

The calculated freshwater production and lifecycle costs are summarized in Table S8.

Table S7: Projected freshwater production and lifecycle cost for the RSE systems at different nominal installation scales.

Parameter	20 m ²	50 m ²	100 m ²
Number of RSE units	2500	3600	12300
Daily freshwater production (m ³ day ⁻¹)	0.440	1.109	2.166
Annual freshwater production (m ³ year ⁻¹)	160.67	404.89	790.50
20-year freshwater production (m ³)	3213.42	8097.82	15810.02
RSE unit cost (USD)	1250.00	3150.00	6150.00
CF substrate cost (USD)	6.00	15.00	30.00
CNT cost (USD)	562.50	1417.50	2767.50
Condensation device cost (USD)	1650.00	4125.00	8250.00
Initial system cost (USD)	3468.50	8707.50	17197.50
Cost per replaceable RSE set (USD)	1818.50	4582.50	8947.50
Number of RSE sets used over 20 years	40	40	40
Cumulative 20-year cost (USD)	74390	187,425	366,150
Preliminary LCOW (USD m ⁻³)	23.15	23.15	23.16

Note S9.5 Preliminary levelized cost of water

For comparison with economic metrics reported for solar desalination technologies, the levelized cost of water can generally be expressed as [2]

$$LCOW = [I_0 + \sum_{t=1}^n C_t / (1 + i)^t] / [\sum_{t=1}^n V_t / (1 + i)^t] \tag{22}$$

where I_0 is the initial investment, C_t is the operating, maintenance, and replacement cost in year t , V_t is the freshwater production in year t , i is the discount rate, and n is the system lifetime.

Because the present study represents a laboratory-derived scale-up projection rather than a financed engineering project, a site-specific discount rate was not assigned. The base-case calculation therefore uses $i = 0$, under which Equation (22) reduces to

$$LCOW_{pre} = C_{total} / V_{total} \tag{23}$$

Accordingly, after 20 years of projected operation, the preliminary LCOW values of the nominal 20, 50, and 100 m² systems were approximately 23.15, 23.15, and 23.16 USD m⁻³, respectively.

The nearly identical values obtained for the three installation scenarios result from the approximately linear scaling of both component cost and freshwater production adopted in the present model. Therefore, the current calculation does not assume an economy-of-scale benefit for increasing the installation area. The 20, 50, and 100 m² cases should instead be regarded as different modular deployment scenarios.

Within the present economic boundary, repeated replacement of the RSE-related components represents the

dominant contribution to the 20-year lifecycle expenditure. Thus, extending the operating lifetime of the evaporator components and increasing the experimentally collected freshwater yield are expected to be important factors for reducing the projected LCOW.

Note S9.6 Comparison with reported solar desalination costs

To provide context for the economic projection, the preliminary LCOW of the RSE was compared with representative solar desalination systems and published cost ranges. The comparison is summarized in Table S10.

Table S8: Comparison of the projected water cost of the RSE with representative solar-powered desalination systems reported in the literature.

System	Technology	Reported water cost or LCOW (USD m ⁻³)	Economic context	Reference
RSE, this work	Direct solar interfacial evaporation	23.15–23.16	Preliminary 20-year lifecycle projection, $i = 0$	This work
Thermoelectric-field-enabled evaporator	Solar interfacial evaporation	~1–3	Techno-economic LCOW analysis	Ref. [3]
CSP-driven thermal desalination	Concentrated solar thermal desalination	0.94–4.31	Reported LCOW range for solar thermal desalination configurations	Ref. [4]
Solar still	Direct solar desalination	1.4–6.5	Reported renewable-energy desalination cost range	Ref. [5]
Solar membrane distillation	Solar-driven membrane distillation	10.4–19.5	Reported renewable-energy desalination cost range	Ref. [5]
PV-powered seawater RO	Photovoltaic reverse osmosis	11.7–15.6	Reported renewable-energy desalination cost range	Ref. [5]

The comparison shows that the present preliminary RSE cost remains higher than those reported for several optimized solar desalination systems. This difference should be interpreted in the context of the conservative six-month replacement interval adopted for the RSE components and the relatively small experimentally validated freshwater production scale. Previous analyses have also shown that reported solar desalination costs vary substantially with system size, lifetime, financing assumptions, component replacement, manufacturing cost, operating expenditure, and the definition of freshwater productivity [2].

Therefore, Table S10 is intended to provide an economic context rather than a direct ranking of different technologies. The current RSE analysis demonstrates how experimentally measured modular freshwater production translates into lifecycle water cost under explicitly defined assumptions. A complete techno-economic analysis will require pilot-scale information on manufacturing and assembly costs, long-term component lifetime, actual maintenance requirements, site-specific operating conditions, financing parameters, and system-level freshwater recovery. These parameters will be incorporated when sufficiently long-term and large-area operating data become available.

Table S9: Performance comparison with previously reported solar evaporators.

	Evaporation rate (kg m ⁻² h ⁻¹)	Energy efficiency (%)	References
This work	1.74	108.75	
AMBG	2.88	>93	Ref. [6]
SSA	2.22	93.5	Ref. [7]
BC _{Cu} @FC	1.571	87.05	Ref. [8]
MPE	1.75	98	Ref. [9]
PVA/APTES-Cu-Mn/H	2.48	94.83	Ref. [10]
QFPAM	2.21	131.4	Ref. [11]
CFs@MF/Fe-P	1.82	87.96	Ref. [12]
CzTFCT	1.975	92.5	Ref. [13]
MCPWC	2.99	97.06	Ref. [14]
APGD-ssPCM	1.24	87.28	Ref. [15]
CNF/PLA/PDAN	1.5	90	Ref. [16]
PPy-PI NAG	1.42	95.98	Ref. [17]
CTS@CTS/CNT	1.547	91.47	Ref. [18]
MGA	1.72	86.5	Ref. [19]
AP/CS-Ppy	1.865	85.96	Ref. [20]
TA hydrogel	1.897	89.7	Ref. [21]

Table S10: Comparison of salt-management strategies, operational stability, and practical features of representative solar evaporators.

	Salt/thermal-management strategy	Extended-operation stability	Practical/cost-related feature
This work	Water-level-regulated salt localization in the central valley; raised-water-level redissolution; opposing ridge surfaces enable radiative heat recovery	14 crystallization–dissolution cycles; 89.8% evaporation-rate retention; >99% salt dissolution efficiency; 28 d outdoor operation	Simple modular ridge structure; preliminary LCOW ≈23.15 USD m ⁻³
AMBG	Geometry-angle coupling establishes bidirectional heat transport and directs salt crystallization toward the edges	Long-term stability reported under high-salinity conditions	Structurally regulated salt and heat transport; quantitative LCOW not reported
SSA	Spatially decoupled photothermal and evaporation interfaces suppress salt deposition	Stable for 15 d, 8 h d ⁻¹ , without salt crystallization	Reverse-side evaporation improves condensate collection; outdoor freshwater yield 6.08 kg m ⁻²
BCCu@FC	Large porous FC network promotes salt-ion convection/diffusion back toward bulk water	No obvious salt crust after 24 h in 3.5 wt% brine; stable in 21 wt% brine; deposited salt redissolved within 4 h after illumination ceased	Simple two-step preparation; described as cost-effective
MPE	Joule-assisted photothermal heating and magnetic regulation; no dedicated active salt-routing strategy reported	Stable vapor generation reported; quantitative long-term salt-cycling data not specified	Rapid fabrication and relatively low cost
PVA/APTES-Cu-Mn/H	Vertically aligned microchannels promote water transport and vapor escape; hydrogel exhibits salt rejection	Stable evaporation in 20 wt% brine; outdoor freshwater production ≈13.04 kg m ⁻² d ⁻¹	Integrated evaporation and photocatalytic purification

QFPAM	Cone/plate geometry suppresses conduction-induced heat loss; no dedicated active salt-regulation mechanism reported	Seawater evaporation demonstrated, including 5.68 kg m ⁻² water evaporation under cloudy conditions; extended salt-cycling not specified	Structure-based thermal management
CFs@MF/Fe-P	Surface hydrophobicity and interconnected transport channels inhibit surface salt accumulation	Salt accumulation suppressed during prolonged evaporation in 15 wt% saline solution	Bio-derived collagen fibers; described as low-cost and sustainable
CzTFCT	3D porous PU supports photothermal conversion; no dedicated salt-routing strategy reported	Quantitative long-term salt-cycling test not specified in the accessible report	Cost-effective organic cocrystal; simultaneous freshwater/electricity generation
MCPWC	Tree-inspired porous water transport combined with photothermal evaporation and photocatalysis; no specific active salt-management strategy reported	Outdoor water purification demonstrated; quantitative salt-cycling duration not specified	Self-floating integrated evaporation/photocatalytic system
APGD-ssPCM	Solid-solid phase-change material stores and releases thermal energy to extend evaporation beyond illumination periods	Outdoor evaporation of 33.72 kg m ⁻² d ⁻¹ ; evaporation rate remained 0.97 kg m ⁻² h ⁻¹ after 6 h without illumination	Grafting-based phase-change heat storage; continuous solar utilization
CNF/PLA/PDAN	Porous hydrophilic aerogel enables water transport; no dedicated active salt-routing mechanism reported	Cycling stability reported	Green multifunctional aerogel; simultaneous Ag ⁺ reduction
PPy-PI NAG	Hierarchical nanofiber pores promote water transport and salt removal back toward bulk water; low thermal conductivity localizes heat	Stable desalination for 15 d; evaporation performance retained after 1000 compression/folding cycles	Scalable, portable evaporator
CTS@CTS/CNT	Hydrophilic outer layer supplies water while hydrophobic core provides thermal insulation; no dedicated directional salt-crystallization strategy	High stability and recyclability during desalination; long-term cycles reported qualitatively	Simple all-in-one preparation
MGA	Vertical porous channels enable water transport; self-desalination behavior suppresses salt accumulation	Stable evaporation rate and efficiency over 15 evaporation cycles	One-step hydrothermal preparation; reported as simple and low-cost
AP/CS-Ppy	Porous chitosan/anode-powder aerogel provides	Stable treatment of seawater and highly concentrated	One-step hydrothermal preparation; reported as

	salt resistance in concentrated saline solutions	saline solutions; exact cycle duration not specified	simple and low-cost
TA hydrogel	Hydrophilic hydrogel enables continuous water transport; no dedicated directional salt-regulation strategy	Stable for 12 h and 20 evaporation cycles without obvious decline	Eco-friendly, low-cost raw materials and simple blending preparation

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