Supplementary Information

A Salt-Rejecting, Floating Solar Vapor Generator for Low-Cost Desalination

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Experimental Details

The floating solar still was designed to be low cost and easily manufactured from widely available materials. The evaporation structure was constructed from cellulose-based fabric (Zorb®), and expanded polystyrene (Owen-Corning Foamular® 150). The condensation structure was constructed from lightweight and cheap polymer films. We evaluated several polymer films, eventually settling on commercial polyester films (McMaster-Carr #8567K32, 0.003” thick). The film was cut into several pieces, and welded together using a heat sealer (McMaster-Carr #2054T35). Droplet collection was facilitated using flaps of polyester film and fabric wicks (Zorb®), as an alternative to typical rubber drip edges and tubes. The polyester film was supported by plastic rods and joints. The wholesale materials cost of the entire floating solar still including evaporation structure and cover is ~ $3 m⁻².

The evaporation structure was tested in the lab using a solar simulator (ScienceTech, SS-1.6K) outputting simulated solar flux at 1000 Wm⁻² (1 sun). The solar flux was measured using a thermopile (Newport, 818P-040-55) connected to a power meter (Newport, 1918-C). Because the solar flux varies across the beam area, and the thermopile detector is smaller in area than the solar receiver, the solar flux was measured over 5 distributed locations and averaged. The evaporation structure was placed in a polycarbonate basin (21 cm x 22 cm x 3.5 cm), filled with fresh water or saline water. The mass loss of the water was measured using a balance with 0.1 g resolution (A&D, EJ3000). Steady-state evaporation rates were measured for 30 minutes once steady conditions were reached.

The temperatures were measured at five different locations of the evaporation structure shown in Fig. 2d (T₁: at the black absorber, T₂: wick below the absorber, T₃: underneath the thermal insulation, T₄: in the wick bottom of the evaporation structure, and T₅: in the bulk of the liquid) using thermocouples (Omega Engineering, 5TC-TT-K-40-36), and recorded using an Omega Engineering DAQPRO. The absorber temperature was measured by a thermocouple inserted into the evaporation fabric. Thermocouples were placed at the center, to represent the temperature of
a sufficiently large absorber where side effects would be negligible. In Fig. 5c, only four different temperatures are measured, with the bottom of the thermal insulation not measured. The temperatures measured are: $T_1$ at the black absorber, $T_2$ wick below the absorber, $T_3$ in the wick bottom of the evaporation structure, and $T_4$ in the bulk of the liquid.

For the day-to-day salt rejection experiments, water with 3.5 wt% NaCl was premixed and placed in the basin, which acted as a salt reservoir. For the week-long salt rejection experiment, the evaporation structure and salt reservoir were exposed to sunlight at 1 kWm$^{-2}$ for 5 hours each day, then allowed to cool and reject salt for 19 hours. The mass of the entire system was monitored to determine the amount of water evaporated. Fresh water was added, as needed to the bottom of the salt reservoir at the beginning of experiment each day, to ensure the reservoir’s NaCl concentration remained constant at the start of each day. The evaporation structure surface was photographed daily to monitor the nucleation of NaCl crystals.

The saturation salt rejection experiments were conducted using a glass container with 2.9 L capacity (18 cm in diameter). Water with 3.5 wt% NaCl was premixed and placed in the glass container, which acted as a salt reservoir. A small (14 cm x 7 cm) evaporation structure was used. The small size was chosen to ensure the NaCl rejected to the reservoir wouldn’t significantly change the reservoir’s NaCl concentration. The area between the structure and the container was covered with a plastic cover. The entire setup was exposed to 1 kWm$^{-2}$ of sunlight, and then 40 g of salt crystals were deposited on top of the evaporation structure. A camera periodically photographed the evaporation structure surface to show salt dissolving and rejecting over the course of a few hours. The salt concentration of the reservoir and evaporation structure top was measured using an optical refractometer with a resolution of 0.1 wt% NaCl (ATC SSA0010). A few drops (3 to 4) of liquid were sucked from the measurement location, and deposited onto the optical window of the refractometer. The final salt concentration in the salt water was 4.6 wt% after the salt rejection experiment.

Rooftop water collection measurements were performed with the large solar still (55 cm x 55 cm). The solar intensity (global horizontal irradiance) was measured using a Hukseflux LP-02 thermal pyranometer. The floating solar still was placed in a shallow basin of water (3 cm deep), placed on a table to avoid conductive heating from the rooftop surface. The floating solar still was oriented with the sloped panels facing south. Water collected from the still was routed via a tube to several sealed beakers. The beakers were emptied 2-3 times throughout the day, and the mass of water collected was recorded. The water collection was recorded through a 24-hour period, starting after sunset when the solar still had equilibrated to ambient temperature.

The ocean experiments were conducted in Pleasure Bay, located in South Boston, MA. The bay is connected to the Atlantic Ocean, and has a salinity of 3 wt%, as measured by the optical refractometer. The temperatures at different locations of the evaporation structure (shown in Fig. 5d of manuscript) and the ocean water were measured using thermocouples (Omega Engineering, 5TC-TT-K-40-36) and the Omega DAQPRO. The solar flux data was provided using a local weather station maintained by the MIT Sustainable Design Lab. The liquid water produced by the floating solar still was collected in submerged water bottles. The collected water was weighed at the end of the experiment to determine amount produced, and the salinity was measured using an optical to ensure that no seawater had leaked in. The salinity measured was below the lowest readable limit on the refractometer, 0.1 wt% NaCl. The purity of the water is expected to be very pure, due to a standard evaporation process being used without any bubbling and aerosolizing of the heated liquid. Typical distilled liquids are 1-50 ppm in purity.
Supplementary Notes S.1

Wick to Insulation Area Ratio Using Diffusion Assumption

To aid in the choice of the wick-to-insulation ratio for the evaporation structure, we estimate the minimum wicking area needed, by assuming diffusion through the wick. In reality, some advection occurs in the porous fabric, but the diffusion limit serves as a conservative estimate for the required wick area.

We estimate the NaCl rejected in one solar day, given expected evaporation rates, while avoiding NaCl crystallization on the evaporation structure. Fick’s law is used to calculate NaCl diffusion flow from the top of the insulation structure, where excess NaCl is “generated”, through the narrow wick, and finally to the bottom of the insulation structure, where natural and forced convection from the body of water quickly disperse the rejected salt. The mass flow rate of NaCl through the wick is given by

\[ J = D_{NaCl} A_{wick} \rho_w \frac{(C_{evap} - C_\infty)}{l_w}, \]  

(S-1)

where \( D_{NaCl} \) is the diffusion coefficient of NaCl in water, taken to be \( 1.99 \times 10^{-9} \text{ m}^2 \text{s}^{-1} \), \( C_{evap} \) and \( C_\infty \) are the mass fraction of salt to water at the evaporation surface \( evap \) and at and bottom \( \infty \), and \( \rho_w \) is the partial density of water in the solution. \( l_w \) is the length of the wick (2 cm). The NaCl concentration at the top of the insulation structure is assumed to be saturated, the maximum allowable concentration before salt nucleation, corresponding to 26 wt\% or (~350 NaCl ppt of water). At the bottom of the insulation structure, the NaCl concentration is assumed to be 3 wt\%, similar to seawater. The bottom NaCl concentration is considered constant, because the intended operation of this floating solar still is large bodies of saline water.

The required NaCl mass flow is determined by estimating the excess NaCl generated \( m_{exc} \) by the evaporation structure with area \( A_{evap} \) over one full day of operation, assuming 22% solar-to-water energy conversion \( \eta_{evap} \), and allowing for NaCl rejection to occur over 24 hours \( (t_{day}) \).

\[ m_{exc} = A_{evap} \frac{\eta_{evap} E_{solar}}{h_f g} \times \frac{3 \text{ wt\%}}{97 \text{ wt\%}}, \]  

(S-2)

where \( E_{solar} \) is the total solar insolation in one day (kW hr m\(^{-2}\)). The wick-to-evaporation area ratio \( (A_{wick}/A_{evap}) \) needed is then solved using the following expression:

\[ \frac{A_{wick}}{A_{evap}} = \frac{\eta_{evap} E_{solar} \times 3 \text{ wt\%}}{D_{NaCl} \rho_w \frac{(C_{evap} - C_\infty)}{l_w} t_{day}}. \]  

(S-3)

For an area similar to Boston, USA, which receives roughly 5 kW hr of sunlight per day annually, we determine the maximum wick area needed to avoid salt nucleation is 22% of the total area. The rest of the thermal insulation structure is taken up by the expanded polystyrene. Our experimental results showed that convection plays a significant role in salt rejection, hence evaporation efficiency can be enhanced by reducing the wick area.
Comparison of Diffusion vs. Advection Differences between Thermal and Chemical Transport

Salt needs to be removed from the evaporation surface, which can be achieved either by diffusing salt away to the ocean (diffusion) or by washing the evaporation surface with additional ocean water (advection). At first look, advection appears to be a poor choice, given that advection implies higher heat losses, reducing the performance of the system. Diffusion occurs in still waters, and intuitively, still water leads to less heat loss since conduction is less effective than convection.

However, the important consideration is the amount of heat loss per salt molecule rejected. Although water advection leads to high heat losses, it also leads to a high salt rejection rate. If we reduce the overall flow of water, then advection heat losses are reduced as well. We argue here that the use of diffusion or advection is dependent on material properties of the salt and solvent pair, NaCl and water in this case.

We start with a diffusion-based system, as shown in Figure S.1a. The evaporation temperature $T_{\text{evap}}$ is fixed, and we assume the salt concentration of the reservoir (ocean) $C_\infty$ and the ambient temperature $T_\infty$ are known. The steady-state energy balance at the evaporation surface is:

$$Q_{s,d} = \dot{m}_{\text{evap}} (h_{fg} + c_p T_{\text{evap}}) - \dot{m}_{in} c_p T_\infty + \frac{k_w}{l_w} A_{\text{wick}} (T_{\text{evap}} - T_\infty) + Q_{\text{loss}}.$$  \hspace{1cm} (S-4)

where $Q_{s,d}$ is the total input heat required to sustain the system, $\dot{m}_{\text{evap}}$ is the water evaporation rate (kg/s), $h_{fg}$ is the latent heat of vaporization of water, $c_p$ is the specific heat of water, $A_{\text{wick}}$ is the area of the wick, $k_w$ is the thermal conductivity of water, $l_w$ is the length of the wick, and
\( \dot{m}_{lw} \) is the rate of water wicking up in the wick to the absorber surface (kg/s). The first term is the enthalpy leaving through vapor, the second term is the enthalpy wicked up by liquid water, and the third term is the conduction heat losses through the wick. The contribution of NaCl to the heat capacity is neglected, due to a much lower specific heat and lower mass fraction than water. In addition, parasitic losses such as radiative and convective losses are lumped into a \( Q_{\text{loss}} \) term.

Since mass is conserved, \( \dot{m}_{in} = \dot{m}_{evap} \), and

\[
Q_{s,\text{d}} = \dot{m}_{evap} (h_f + c_p (T_{\text{evap}} - T_\infty)) + \frac{k_w}{l_w} A_{\text{wick}} (T_{\text{evap}} - T_\infty) + Q_{\text{loss}}
\]

\[
= h_{evap} A_{evap} (T_{\text{evap}} - T_\infty) + \frac{k_w}{l_w} A_{\text{wick}} (T_{\text{evap}} - T_\infty) + Q_{\text{loss}},
\]

where \( h_{evap} \) is an effective evaporation heat transfer coefficient between the evaporation surface (area \( A_{evap} \)) and ambient air:

\[
h_{evap} = \frac{\dot{m}_{evap}}{A_{evap}} \left( \frac{h_f}{T_{\text{evap}} - T_\infty} + c_p \right)
\]

In the steady state condition, for the diffusive system, the salt conservation equation is:

\[
\dot{m}_{evap} C_\infty = \frac{D_{\text{NaCl}} A_{\text{wick}} \rho_w}{l_w} (C_{evap} - C_\infty),
\]

where \( D_{\text{NaCl}} \) is the diffusion coefficient \((m^2/s)\) of NaCl in water and \( \rho_w \) is the average partial density of water in the wick, \( C \) is the local mass fraction of salt to water, and the subscripts \( evap \) and \( \infty \) denote evaporation surface and reservoir. The left hand side is the salt accumulation rate on the absorber and the right hand side is the diffusion rate downward.

For the wick length one can write

\[
l_w = \frac{D_{\text{NaCl}} \rho_w A_{\text{wick}}}{\dot{m}_{evap} C_\infty} (C_{evap} - C_\infty),
\]

\( l_w \) is determined and maximized by setting \( C_{evap} = C_{\text{sat}} \) \( (\frac{m_{evap}}{A_{\text{wick}}} \) is constant), which minimizes the heat conduction loss

\[
Q_d = \frac{k_w}{l_w} A_{\text{wick}} (T_{\text{evap}} - T_\infty).
\]

The salt rejected via diffusion is then

\[
J_d = \frac{D_{\text{NaCl}} \rho_w A_{\text{wick}}}{l_w} (C_{\text{sat}} - C_\infty).
\]

\( Q_d \) is the heat flow through the wick via diffusion, \( J_d \) is the salt flow diffused through the wick. The ratio of diffusion heat loss to salt diffusion is
This ratio should then be compared with a similar ratio for an advection system, \( \frac{Q_{adv}}{J_{adv}} \), the ratio of advective heat flux to advective salt flux.

For the advection system, the heat and salt flows are calculated using the same conditions, i.e., \( T_{evap} \) and \( T_\infty \) are fixed, \( \dot{m}_{evap} \) is fixed, \( C_\infty \) is fixed, and \( C_{evap} \leq C_{sat} \). Again, the NaCl contribution to heat capacity is neglected. Figure S.1b describes the energy and mass transport circuit. The energy balance on the advection system is

\[
Q_{s,adv} = \dot{m}_{evap} (h_g + c_p T_{evap}) + \dot{m}_{out} c_p T_{evap} - \dot{m}_{in} c_p T_\infty + Q_{loss}. 
\]  
(S-11)

Since mass is conserved, \( \dot{m}_{in} = \dot{m}_{out} + \dot{m}_{evap} \) and

\[
Q_{s,adv} = \dot{m}_{evap} (h_g + c_p (T_{evap} - T_\infty)) + \dot{m}_{out} c_p (T_{evap} - T_\infty) + Q_{loss}. 
\]  
(S-12)

Again, the heat loss from evaporation can be modeled with an effective evaporation heat transfer coefficient \( h_{evap} \)

\[
Q_{s,adv} = h_{evap} A_{evap} (T_{evap} - T_\infty) + \dot{m}_{out} c_p (T_{evap} - T_\infty) + Q_{loss}, 
\]  
(S-13)

where

\[
h_{evap} = \frac{\dot{m}_{evap}}{A_{evap}} \left( \frac{h_g}{T_{evap} - T_\infty} + c_p \right). 
\]

The second term is the advective heat loss, \( Q_{adv} \).

\[
Q_{adv} = \dot{m}_{out} c_p (T_{evap} - T_\infty). 
\]  
(S-14)

\( \dot{m}_{out} \) needs to reject the excess salt left by the evaporation process. In steady-state condition, one can write the mass balance for the salt flux

\[
\dot{m}_{in} C_{\infty} = \dot{m}_{out} C_{evap}. 
\]  
(S-15)

Using mass conservation, \( \dot{m}_{in} = \dot{m}_{out} + \dot{m}_{evap} \), one finds

\[
\dot{m}_{out} C_{\infty} + \dot{m}_{evap} C_\infty = \dot{m}_{out} C_{evap}, 
\]  
(S-16)

and

\[
\dot{m}_{out} = \frac{\dot{m}_{evap} C_\infty}{(C_{evap} - C_\infty)}. 
\]  
(S-17)

\( \dot{m}_{out} \) should be minimized to minimize advective heat loss, while ensuring \( C_{evap} \) does not exceed the saturation concentration \( C_{sat} \).
\[ m_{\text{out}} = \frac{m_{\text{evap}} c_{\infty}}{(c_{\text{sat}} - c_{\infty})}. \]  

(S-18)

With \( m_{\text{out}} \) determined, the advective heat loss is fully determined

\[ Q_{\text{adv}} = \frac{m_{\text{evap}} c_{\infty}}{(c_{\text{sat}} - c_{\infty})} c_p (T_{\text{evap}} - T_{\infty}). \]  

(S-19)

To determine the salt rejected by advection, we consider again \( m_{\text{out}} \),

\[ m_{\text{out}} = \frac{m_{\text{evap}} c_{\infty}}{(c_{\text{sat}} - c_{\infty})}, \]  

(S-20)

and

\[ J_{\text{adv}} = m_{\text{out}} (c_{\text{sat}} - c_{\infty}), \]  

(S-21)

where \( J_{\text{adv}} \) is the salt rejection needed to sustain evaporation rate, \( m_{\text{evap}} \). If we compare the ratio of heat and salt advected away,

\[ \frac{Q_{\text{adv}}}{J_{\text{adv}}} = \frac{m_{\text{out}} c_p (T_{\text{evap}} - T_{\infty})}{m_{\text{out}} (c_{\text{evap}} - c_{\infty})} = \frac{c_p (T_{\text{evap}} - T_{\infty})}{(c_{\text{sat}} - c_{\infty})}. \]  

(S-22)

If we compare this ratio to the similar ratio for diffusion,

\[ \frac{Q_{\text{d}}}{J_{\text{d}}} = \frac{Q_{\text{conv}}}{J_{\text{conv}}} = \frac{k_T (T_{\text{evap}} - T_{\infty})}{D_{\text{NaCl}} (c_{\text{sat}} - c_{\infty})} = \frac{\alpha_w}{D_{\text{NaCl}}} \]  

(S-23)

where \( \alpha_w \) is the thermal diffusivity of water. This figure of merit states that for any given vapor generation \( m_{\text{evap}} \) at \( T_{\text{evap}} \), the ratio of heat loss by advection vs. diffusion is determined purely by the material properties. In the diffusive case, we compare thermal conductivity and salt diffusion coefficient, while for the advective case we compare the volumetric heat capacity. For water, \( \alpha_w = 1.43 \times 10^{-7} \) m\(^2\)/s, and \( D_{\text{NaCl}} = 1.99 \times 10^{-9} \) m\(^2\)/s and the figure of merit is 0.01, suggesting that the better approach to salt rejection in solar evaporation is advection. It is worth pointing out that our analysis is based on saturation salt concentration at the solar absorption surface, but this analysis is also valid for smaller concentrations.
A heat transfer model was developed for the entire floating solar still, including the condensation cover and evaporation structure. The model is based on energy balance at two points, the evaporation structure and the condensation cover. $T_{evap}$ represents the top of the evaporation structure (absorber), $T_c$ represents the cover temperature, and $T_\infty$ the ambient temperature.

The steady-state energy balance equation for the evaporation structure is:

$$q_{solar} \alpha_{evap} \tau_c A_{evap} = Q_{side} + A_{evap} q_{cond} + A_{evap} q_{rad} + A_{evap} q_{evap} + A_{evap} q_{conv}, \quad (S-24)$$

and energy balance for the still cover is:

$$(q_{conv} + q_{rad} + q_{evap}) A_{evap} = (q_{rad,c-a} + q_{conv,c-a}) A_c, \quad (S-25)$$

where $q_{solar}$ is the incident solar flux, $\alpha_{evap}$ is the solar absorptance of the evaporation structure; $\tau_c$ is the transmittance of the floating solar still cover; $q_{rad}$, $q_{conv}$, and $q_{evap}$ are the radiation, convection and evaporation heat fluxes between the evaporation structure and the cover; $q_{cond}$ is the conduction heat flux from the evaporation structure to the underneath water; $Q_{side}$ is the total heat loss from the side of the evaporation structure; $q_{rad,c-a}$ and $q_{conv,c-a}$ are the radiation and convection heat fluxes between the cover and the ambient; and $A_{evap}$ and $A_c$ are the area of evaporation structure (absorber) and the cover, respectively.
The left-hand side of Eq. (S-24) represents solar heat generation to the evaporation structure considering the cover transmission loss and fabric absorptance. The reflection losses from the wet cover (polyester cover covered with condensed droplets) were chosen based on the experimentally measured values ($\tau_c=65\%$). Optical absorptance of the evaporation structure (absorber) was taken as ($\alpha_{evap} = 85\%$), but absorption in the polyester film cover for incident solar energy was neglected. Multiple reflection of the solar radiation inside the still is neglected.

Convection through the air inside the still was estimated using a correlation for natural convection in enclosed horizontal spaces:

$$Nu = \frac{h_{conv}}{k_{air}} = 0.069Ra^{\frac{1}{3}}Pr^{0.075}, \quad (S-26)$$

where $Nu$ is the Nusselt number, $h_{conv}$ is the heat transfer coefficient ($\sim 3 \text{ Wm}^{-2}\text{K}^{-1}$), $k_{air}$ is the thermal conductivity of air ($0.02 \text{ Wm}^{-1}\text{K}^{-1}$), $l_c$ is the vertical distance of the enclosed volume, $Ra$ is the Rayleigh number, and $Pr$ is the Prandtl number. The convection heat flux inside the still becomes:

$$q_{conv} = h_{conv}(T_{evap} - T_c). \quad (S-27)$$

Radiation heat loss from the evaporator, $q_{rad}$, is calculated using Stefan-Boltzmann law,

$$q_{rad} = \sigma F_{evap-c}(T_{evap}^4 - T_c^4), \quad (S-28)$$

where $\sigma$ is the Stefan-Boltzmann constant. The emittances of $T_{evap}$ and $T_c$ are assumed to be 1 (blackbodies), due to the fact that both cover and evaporation structure being covered with water, which is highly absorbing/emitting in the infrared regime. $F_{evap-c}$ is the viewfactor between evaporation structure and cover, which is assumed 1 because the evaporation structure’s surface does not see itself.

Evaporation and condensation between the evaporation structure and cover is assumed to be dominated by convection flow of water vapor, and not limited by interfacial transport between the liquid and vapor phases. The following correlation is used for the evaporation heat transfer coefficient:

$$q_{evap} = h_{fg}C\rho_{wa}(\rho_{ca} - \rho_{wa})^{\frac{1}{2}}(W_w - W_c). \quad (S-29)$$

where $h_{fg}$ is the latent heat of vaporization for water, $C$ is an empirical constant ($35 \text{ m}^2 \text{ hr}^{-1}\text{ kg}^{-1/3}$), $\rho_{wa}$ is the density of air at the evaporation surface, $\rho_{ca}$ is the density of air at the cover surface, $W_w$ is the specific humidity at the evaporation surface, and $W_c$ is the specific humidity at the cover surface.

Heat conduction through the evaporation structure is calculated using Fourier law. The evaporation structure that includes composite insulation (wick, polystyrene) is modeled using parallel resistances. Although we later show advection of water occurs due to salt rejection, we assume thermal conduction here as a conservative estimate of heat loss.
\[ q_{\text{cond}} = \frac{k_{\text{eff}}}{I_w} (T_{\text{evap}} - T_{\infty}). \]  
(S-30)

\[ k_{\text{eff}} = \frac{k_w A_w + k_{\text{ins}} A_{\text{ins}}}{A_w + A_{\text{ins}}}. \]  
(S-31)

The wick is modeled as water \((k_w, 0.58 \text{ Wm}^{-1}\text{K}^{-1})\), and \(k_{\text{ins}}\) is the thermal conductivity of polystyrene foam \((k_{\text{ins}}, 0.02 \text{ Wm}^{-1}\text{K}^{-1})\). The heat conduction flows to the water underneath, which is modeled as ambient temperature, \(T_{\infty}\). This assumes the water flow in real situations imposes a negligible thermal resistance of convection in water (the heat transfer coefficient for forced convection in water is typically hundreds of \(\text{Wm}^{-2}\text{K}^{-1}\)). The wick’s height is \(I_w\).

The heat losses to the side of the floating still, \(Q_{\text{side}}\), were determined using the COMSOL model (section S.5). For a 55 cm x 55 cm floating solar still, the side losses are conservatively estimated to be 10% of the losses from the top of the evaporation structure. This is reflected by using an effective side area, \(A_{\text{side}}\), \((A_{\text{side}} = 0.1A_{\text{evap}})\).

\[ Q_{\text{side}} = A_{\text{side}} (q_{\text{conv}} + q_{\text{rad}}). \]  
(S-32)

For the convective heat flux between the cover and ambient one can write

\[ q_{\text{conv},c-a} = h_c(T_c - T_{\infty}), \]  
(S-33)

where \(h_c\) is the external heat transfer coefficient. Here, forced convection due to wind \((h_c)\) is modeled using a heat transfer coefficient of 30 \(\text{W m}^{-2}\text{K}^{-1}\).

The radiation heat flux between the cover and ambient is

\[ q_{\text{rad},c-a} = \sigma F_{c-a} (T_c^4 - T_{\infty}^4) \]  
(S-34)

assuming the cover can be modeled as a blackbody due to being covered with water droplets that are opaque in the infrared (optical depth ~0.1 mm), and the droplets being thin enough (~1 mm) that it is isothermal with the cover and is not a limiting thermal conductance in the heat flux path. The view factor \(F_{c-a}\) is assumed 1 due to the cover not viewing itself.

Equations (S-24) and (S-25) form a close system of equations that can be solved iteratively for \(T_c\) and \(T_{\text{evap}}\). Once \(T_c\) and \(T_{\text{evap}}\) are known, \(q_{\text{evap}}\) can be determined.

The water collection efficiency \(\eta_{\text{water}}\) of the floating solar still is determined by

\[ \eta_{\text{water}} = \frac{\gamma_{\text{coll}} q_{\text{evap}}}{q_{\text{solar}}}, \]  
(S-35)

where \(\gamma_{\text{coll}}\) is the area ratio of collectable area to condensable area in the cover (not all condensed droplets can be collected). Note that in the mathematical formulation vapor leakage was neglected.

Using this steady–state system model, comparisons with the ocean water collection experiments were made vis-à-vis the solar-weighted, daily-average intensity and ambient air temperature. In the summer, the average solar intensity was typically 750 \(\text{Wm}^{-2}\). The daily water collection predicted by the model was within a few percent of the actual collection (24% predicted vs 21-24%...
measured). The calculated absorber ($T_{evap}$) and the cover temperature ($T_c$) using instantaneous solar flux were in agreement with the measured peak temperatures (47°C predicted vs 46±2°C measured). The model inputs are: $q_{solar} = 1000 \text{ W/m}^2\text{K}$, $\alpha_{evap} = 0.85$, $\tau_c = 0.65$, $A_{abs} = 1 \text{ m}^2$, $A_c = 1.44 \text{ m}^2$, $\gamma_{coll} = 0.847$, $h_{fg} = 2403000 \text{ J/kg}$, $T_\infty = 302 \text{ K}$, $h_c = 30 \text{ W/m}^2\text{K}$, and $h_{conv} = 3 \text{ W/m}^2\text{K}$. 
Supplementary Notes S.4

Optical Properties

Figure S.3 shows the optical reflectance data for the dyed cellulose fabrics (Zorb®) used as a solar absorber in the evaporation structure, and the dry polyester film used in the floating solar still cover. The polyester film with droplets was not measured in the spectrophotometer due to the vertical orientation of the sample aperture, which would cause the droplets to shed off. The wet polyester film (film covered by droplets) transmission used in the solar still heat transfer model was measured using a calibrated thermopile (Newport, 818P-040-55) and a solar simulator (ScienceTech, SS-1.6K).

![Figure S.3. Optical properties of the evaporation structure. a) The total reflectance (diffuse + specular) of wet and dry Zorb®, which is used in the evaporation structure to absorb sunlight. b) The total transmission (diffuse + specular) of the dry polyester film used in the floating solar still](image)

We experimentally quantified the optical loss due to condensed droplets by measuring the transmission through a droplet-coated cover using a thermopile power meter. A smaller lab-scale plastic cover was used, and simulated sunlight was used to ensure constant power. The dry polymer cover reflects only 10% of the incoming sunlight, but condensed droplets increase losses to ~35%. Glass covers reflect ~10% (comparison in Figure S.4), although they are much more expensive. Large gains in water production could be achieved by reducing this optical loss.
Figure S.4. The total transmission (diffuse + specular) of dry and wet polyester covers used in the floating solar still and for comparison, the transmission of dry and wet glass.
Supplementary Notes S.5

Cost Analysis

Figure S.5. Bill of materials for the solar still. The entire cover can be disassembled by hand, and stored in a compact space.

The floating solar still was designed with low system cost in mind. The design is entirely polymer and fabric based. The materials list includes 3/8-inch polypropylene rods (McMaster-Carr, #8658K52), acetal connectors, 0.003-inch thick clear polyester film (McMaster-Carr, #8567K32), cellulose fabric (Zorb®, Wazoodle Fabrics), and expanded polystyrene (Owens Corning, Foamular 250). The cost of each part is summarized below using prices of similar items found on Alibaba.com, a wholesale market:

- Polypropylene rods: $1/m² of solar still ($1.5/kg), ~8 m of rod used.
- Acetal joints: $0.10/m² of solar still ($1.5/kg), but cost is probably dominated by manufacturing
- Polyester film: $0.10/m² of solar still ($2/kg), 1.4 m² of film used
- Expanded polystyrene: $1.0/m² of solar still ($60/m³), 2.5 cm thick boards used
- Cellulose fabric: $0.30/m² of solar still ($2/kg), 150 g used
- Plastic tube fittings: $0.40/m² of solar still ($0.10/fitting), 4 used
- PVC tubing: $0.10/m² of solar still ($0.05/meter)

From this estimate, the material cost of the floating solar still is around $3 per square meter of solar still, which can produce 2 L per day. The cost is extraordinarily low. Additional tubing may be needed to connect multiple systems together.

The floating solar still has two advantages: low cost per m³ of water produced, and ability for distributed desalination. The floating solar still has an estimated water production cost of about $1-2/m³. This is based on a two-year lifetime for the system. The cost is on par with reverse osmosis ($0.5-$5/m³ based on scale and salinity) and multi-stage flash ($1-$3/m³), although our cost only considers the materials cost. Our cost is even an order of magnitude lower than traditional single-basin solar stills ($15/m³). The second advantage is that the proposed system is able to produce water at the same price, at small capacities, whereas reverse osmosis costs go up
dramatically at smaller scales (up to $10/m^3$). The floating solar still materials cost is based on area, and scales linearly with production capacity.

Supplementary Notes S.6

Side Losses in Solar Evaporation Experiments

![COMSOL model of the evaporation structure](image)

A COMSOL model was developed to understand the heat flow through the composite insulation structure, made of wick and expanded polystyrene. The simulation mimicked ocean operation conditions. From the simulation, we determined the heat losses from the sides of the evaporation structure to be approximately 6% of the heat losses from the top. In the solar still system heat transfer model (Supplementary Notes S.6), we used 10% to conservatively estimate the side heat losses ($A_{side}$).

The top surface was assumed to absorb 1000 W m$^{-2}$ of incident solar flux, while emitting blackbody radiation (emittance $\varepsilon = 1$), and experiencing both convective losses ($h = 10$ W m$^{-2}$ K), and evaporation losses ($h = 20$ W m$^{-2}$ K). The sides were assumed to have convective and radiative losses only. The bottom temperature was set at ambient temperature (293 K), due to forced water convection rapidly cooling the bottom. The wick (thin) and insulation (thick) layers were modeled with the thermal properties of water and foam. The geometric dimensions of the structure were measured from the evaporation structure prototype.
ANSYS Fluent 17.1 was used to study the fluid flow, salt transport, and temperature distribution in a single wick. The energy, momentum, salt transport (advection), and continuity equations were numerically solved by the 3D Finite Volume Method (FVM) to obtain the velocity and temperature distributions throughout the domain of a single wick.

The wick was considered as an enclosure filled with the salt water, as shown schematically in Fig. S.7. It was assumed that there are no heat and mass fluxes on the sidewalls (insulated and impermeable). Additionally, the temperature and local salt concentration on the upper and the lower walls were set to be constant. The no slip condition was applied for all walls. Conduction and natural convection (resulting from the concentration gradient) were considered as the two mechanisms for heat transfer in the enclosure.

Considering the fluid flow to be laminar, steady state, and neglecting the viscous dissipation, the Navier-Stokes equations can be written as follows:

\[
\frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0 \tag{S-36}
\]

\[
\frac{\partial (\rho u^2)}{\partial x} + \frac{\partial (\rho uv)}{\partial y} + \frac{\partial (\rho uw)}{\partial z} = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) \tag{S-37}
\]

\[
\frac{\partial (\rho uv)}{\partial x} + \frac{\partial (\rho vv)}{\partial y} + \frac{\partial (\rho vw)}{\partial z} = -\frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) \tag{S-38}
\]

\[
\frac{\partial (\rho uw)}{\partial x} + \frac{\partial (\rho vw)}{\partial y} + \frac{\partial (\rho ww)}{\partial z} = -\frac{\partial p}{\partial z} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) - \rho g[1 - \beta(T - T_\infty)] \tag{S-39}
\]

where \(\beta\) is the volumetric thermal expansion coefficient, \(T_\infty\) is the operating reference temperature. The energy equation for the liquid is:
\[ \rho C_p (u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z}) = k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right). \]  

(S-40)

The local mass fraction of salt can be determined by solving advection equation for the salt in the solution:

\[ \frac{\partial (\rho u C)}{\partial x} + \frac{\partial (\rho v C)}{\partial y} + \frac{\partial (\rho w C)}{\partial z} = \frac{\partial (\rho D \frac{\partial C}{\partial x})}{\partial x} + \frac{\partial (\rho D \frac{\partial C}{\partial y})}{\partial y} + \frac{\partial (\rho D \frac{\partial C}{\partial z})}{\partial z}. \]  

(S-41)

The variables appearing in equations S-36 to S-41 are defined in Table S.1. It is worth noting that \( \rho \) is the liquid density (salt water) that is spatially varying.

**Table S.1**

| \( u \) | Velocity in \( x \) direction | \( \mu \) | Dynamic viscosity |
| \( v \) | Velocity in \( y \) direction | \( c_p \) | Specific heat transfer |
| \( w \) | Velocity in \( z \) direction | \( \rho \) | Liquid density (water plus dissolved salt) |
| \( P \) | Pressure | \( k \) | Thermal conductivity coefficient |
| \( T \) | Temperature | \( D \) | Mass diffusion coefficient |
| \( g \) | Gravity acceleration | \( \beta \) | Volumetric thermal expansion coefficient |
| \( C \) | Salt concentration |

The Pressure-Based Segregated Algorithm was used to numerically solve the governing equations. The algorithm is an iterative method in which each governing equation is solved decoupled from other equations in sequential steps. In the first step of the iteration, fluid properties including density and viscosity are updated based on the current solution. Then, the pressure equation is derived from the continuity and the momentum equations in such a way that the velocity field, corrected by the pressure, satisfies continuity. After correction of face mass fluxes, pressure, and the velocity field, species transport and energy equations are solved. The algorithm repeats the iterative process until convergence is reached for the solution variables.

In the numerical simulation, the temperature at the upper and lower surfaces were set at 40°C and 20°C, respectively. These two temperatures were chosen based on the experimentally measured values from the salt rejection experiments. The salt concentration at the bottom of the wick was set to \( C_\infty = 3.5 \text{ wt } \% \) (the salt concentration in sea or ocean water). For the salt concentration at the top of the wick, two extreme conditions, \( C_h = 5\% \) and \( C_h = 25\% \) (saturation condition), were considered. The results for these two extreme boundary conditions are shown in Fig S.8 to Fig S.10.

Figure S.8 shows the velocity vector field for the liquid flow inside the wick for the two different top concentrations. As shown in section A-A of Fig. S.7 (0.5 cm x 2.5 cm), velocity vectors in a section perpendicular to \( y \)-axis are aligned with the \( z \)-axis and no circulation is found in this plane for both concentrations, see Fig. S.8a and Fig. S.9b. However, velocity vectors in a section perpendicular to \( x \)-axis, as shown in section B-B of Fig. S.7 (2.5 cm x 40 cm), reveal counter-rotating two-dimensional convection currents in the wick region of the evaporation structure for both concentration conditions. This type of flow pattern is similar to Benard convection for a pure liquid in an enclosures heated from below and it is schematically shown in Fig.1. b of the main manuscript.
Figure S.9 shows the temperature distribution inside the wick in two perpendicular sections (A-A and B-B of Fig. S.7) for the two different top concentrations: $C_h = 5\%$ and $C_h = 25\%$. The simulation results show that the temperature in B-B plane is uniform in the $y$-direction for the low concentration conditions while it is periodically distributed for the higher concentration. The temperature distributions in these figures are used to calculate the heat flux in the wick (based on wick area) for each boundary condition and the results are shown in Fig. S.10. For the low salt concentration, although advection contributes to the salt rejection, the heat transfer mechanism is predominantly conduction. When the salt concentration is increased to 25\%, natural convection induced by the salt concentration gradient (density gradient) also contributes to the heat transfer (heat loss), see Fig. S.10.

Figure S.8. Velocity vector for the liquid flow inside a wick for the two different top concentrations: $C_h = 5\%$ and $C_h = 25\%$. (a) and (b): Velocity vectors in a section perpendicular to $y$-axis of Fig. S.2 (0.5 cm X 2.5 cm). (c) and (d): Velocity vectors in a section perpendicular to $x$-axis of Fig. S.2 (2.5 cm x 40 cm).
Figure S.9. Temperature distribution inside a wick for the two different top concentrations: $C_h = 5\%$ and $25\%$. (a) and (b) Temperature gradient in a section perpendicular to $y$-axis of Fig S.4 (0.5 cm x 2.5 cm). (c) and (d) temperature gradient in a section perpendicular to $x$-axis of Fig S.2 (2.5 cm x 40 cm).
Supplementary Notes S.8

Fouling From Other Ions Present In Seawater

Salt fouling is possible from other ions present in seawater, other than NaCl. These salts, such as various sulfates and carbonate, are major problems in high-throughput desalination technologies like RO and MSF, which have plant lifetime of 10–30 years. However, this work’s floating solar still is designed as a low-throughput and low-cost technology, and thus fouling of these salts is likely to play a lesser role. Table S.2 below shows the various major ions present in seawater.

Table S.2. Major ions present in seawater and their representative concentrations.5

<table>
<thead>
<tr>
<th>Ion</th>
<th>Molarity (mM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na⁺</td>
<td>480.57</td>
</tr>
<tr>
<td>K⁺</td>
<td>10.46</td>
</tr>
<tr>
<td>Mg²⁺</td>
<td>54.14</td>
</tr>
<tr>
<td>Ca²⁺</td>
<td>10.5</td>
</tr>
<tr>
<td>Sr²⁺</td>
<td>0.0928</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>559.40</td>
</tr>
<tr>
<td>SO₄²⁻</td>
<td>28.93</td>
</tr>
<tr>
<td>HCO₃⁻</td>
<td>2.11</td>
</tr>
</tbody>
</table>
From these ions, various sulfates and carbonates can be formed, which have different solubility levels in water. Many are closer to saturation than NaCl, although NaCl forms the bulk of the potential fouling. Several common sulfates are listed below, in Table S.2. From the salt rejection experiments described in the main manuscript, we observed that the highest NaCl concentration in wick does not exceed 4.5%, or a ~50% increase in molar concentration. Because salt rejection is dominated by advection in our demonstrated system, we can assume similar concentration increases for the other salts present in the system. From Table S.3 below, we can see that the sulfates listed below can sustain at least a 50% increase in concentration at the evaporation surface, while remaining soluble in water at 20°C.

Table S.3. Potential salts for fouling present in seawater and their solubility in water.

<table>
<thead>
<tr>
<th>Salt</th>
<th>Solubility in Water (20°C)</th>
<th>Maximum Concentration in Seawater</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaSO₄</td>
<td>15.4mM</td>
<td>10.5mM</td>
</tr>
<tr>
<td>MgSO₄</td>
<td>2,900mM</td>
<td>28mM</td>
</tr>
<tr>
<td>KSO₄</td>
<td>640mM</td>
<td>10.46mM</td>
</tr>
<tr>
<td>NaSO₄</td>
<td>980mM</td>
<td>28mM</td>
</tr>
<tr>
<td>CaCO₃ (calcite)</td>
<td>10.5mM</td>
<td>10.5mM</td>
</tr>
</tbody>
</table>

For carbonates, typical foulants include various forms of CaCO₃, such as calcite, aragonite, and more. These minerals are near solubility limits in seawater, and are typically managed using pH pretreatment in commercial desalination. In this work’s floating solar still, operation occurs directly in the ocean, and pH pretreatment is not viable. However, the concentration of bicarbonate ions in seawater is relatively low (~2mM). In the worst case, assuming no carbonate rejection back into the ocean, carbonate buildup is expected to have little impact. Assuming a molar mass of 100g/mol, CaCO₃ accumulates at a rate of 211 grams per m³ of water produced. Over the two-year lifetime of the floating solar still, the accumulation would be 0.63kg, which is not nearly heavy enough to sink the structure. It is also not expected to clog up the wicks enough to affect performance, although additional study is needed in this area.

Thus, although other ions are present in seawater, and pose potential fouling problems, they are expected to be manageable based on the current floating solar still. However, more study is needed to characterize the fouling potential, such as an investigation into the effects of temperature on the salt rejection process.

References
(4) Bejan, A. Convection Heat Transfer; Wiley.
