Supplementary Information

Solar-driven simultaneous steam production and electricity generation from salinity

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1. Experimental details

CNT ink preparation.¹ Firstly, 3 g commercial CNTs were dispersed in 120 mL mixed H_2SO_4 and HNO_3 ($H_2SO_4/HNO_3 = 3/1$, v/v) solution by sonication for 10 minutes. Then the CNT-acid mixture was refluxed while stirring vigorously for 2 hours in 90 °C oil bath, and cooled at room temperature after the refluxing process. The CNTs extracted from the residual acids were purified by repeating the processes: diluting with deionized water, centrifuging and decanting the solutions. When the supernatant was neutral, the treated CNT was re-dispersed in deionized water with the concentration of 10 mg mL⁻¹ to form CNT ink.

CNT filter paper preparation. A piece of filter paper (WhatmanTM 1004-150 Grade 4 Qualitative Filter Paper, Pore Size: 20-25 μ m, thickness: 0.2 mm) with designed profile (Fig. S1) was immersed in the CNT ink for 5 minutes. After fully adsorbed CNT, the filter paper was taken out and heated at 120 °C for 30 minutes to reinforce the association of the filter paper and CNT. The CNT modified filter paper was stored in deionized water for further use.

The hybrid solar system fabrication. The structure and components is shown in Fig. S2. Two pieces of organic glass (thickness 1 mm) were cutting into required mould. Combing with homemade Ag/AgCl electrodes (thickness 0.3 mm), gaskets (thickness 0.5 mm), Nafion membrane (N117, thickness 0.18 mm), and the CNT filter paper (with a tail of 3 mm × 1.5 cm), the device was constructed tightly by screws. The joint of each component was sealed by polydimethylsiloxane (PDMS, A/B = 10/1, v/v). Eventually, the effective area of Nafion membrane and Ag/AgCl electrodes was controlled at 1 cm² (1 cm × 1 cm). The Ag/AgCl electrode (Fig. S4) was made by electrochemical oxidation of commercial silver foam in 0.6 mol L⁻¹ NaCl at 1.6 V for 2 minutes using Pt as counter electrode.

Characterizations. The morphology and structure of the CNT filter paper and electrodes were characterized by scanning electron microscopy (SEM, FEI Nova

Nano450). The light adsorption of CNT filter paper were performed via Shimadzu UV-Vis NIR Spectrophotometer (UV-3600). The steam generation was measured by floating the hybrid device in a beaker with 0.6 mol L⁻¹ NaCl solution as simulated seawater. The solar light was supplied by a solar simulator (Newport). Different light intensity was obtained by collecting lens. The mass change of water was measured and recorded by a high accuracy balance (Mettler-Toledo, ME204E). The IR images of the hybrid device under solar illumination were taken by with an infrared camera (Flir E40). The concentration of NaCl in the CNT filter after solar irradiation was analyzed by ion chromatograph (881 Compact IC pro, METROHM). The electrical measurements were conducted with an Autolab PGSTAT302N electrochemical workstation. The current-voltage curves of the hybrid device were performed at a scan rate of 100 mV s⁻¹.

2. Supplementary Notes

Note 1. Solar thermal efficiency

The solar thermal efficiency is calculated as:²

$$\eta_{th} = \frac{\dot{m}h_{\rm LV}}{C_{\rm opt}q_i} \tag{1}$$

where \dot{m} is the mass flux, C_{opt} is the optical concentration, q_i is the nominal direct solar irradiation 1 kW m⁻², and h_{LV} is total enthalpy of liquid-vapor phase change (including sensible heat and phase-change enthalpy), can be calculated as:

$$h_{LV} = \lambda + C\Delta T \tag{2}$$

where λ is latent heat of phase change (2260 kJ kg⁻¹), *C* is specific heat capacity of water (4.2 kJ kg⁻¹ K⁻¹), and ΔT denotes the temperature increase of the water.

Note 2. Salinity power

As shown in Supplementary Fig. 5, under a concentration gradient, a potential drop is generated by the redox reaction on the electrode (E_{redox}), and only the diffusion potential (E_{diff}) is contributed by the cation selective membrane. According to the previous works, in the NaCl electrolyte:³

$$E_{redox} = \frac{RT}{F} \ln\left(\frac{c_H \gamma_H}{c_L \gamma_L}\right)$$
(3)
$$E_{diff} = (2t_+ - 1) \frac{RT}{F} \ln\left(\frac{c_H \gamma_H}{c_L \gamma_L}\right)$$
(4)

where t_+ , R, T, F, γ , $c_{\rm H}$, and $c_{\rm L}$ represent the transference number of cations, gas constant, temperature, Faraday constant, activity coefficient of ions, high and low ion concentrations, respectively. $t_+ = 1$ for complete cation selectivity, while $t_+ = 0$ for complete anion selectivity. The voltage detected by sourcemeter is the sum of $E_{\rm redox}$ and $E_{\rm diff}$, which can be expressed as:⁴

$$E_{total} = E_{redox} + E_{diff} = 2t + \frac{RT}{F} \ln\left(\frac{c_H \gamma_H}{c_L \gamma_L}\right)$$
(5)

The maximum output power of the device can be determined from the current-

voltage curves:

$$P_{max} = \frac{1}{4} E_{OC} I_{SC} \tag{6}$$

where E_{OC} and I_{SC} are the open-circuit voltage and short-circuit current, respectively.

In the reverse electrodialysis system, the current from diffusion process can be expressed as:⁵

$$I_{diff} = FAD \frac{\partial C}{\partial x} \tag{7}$$

where A is the diffusion cross area, D is ion diffusion coefficient which is a

temperature sensitive parameter, and $\frac{\partial C}{\partial x}$ is the concentration gradient.

Note 3. Energy efficiency analysis

According to previous literature, the free energy change from mixing a concentrated and a diluted solution can be written as:^{6, 7}

$$\Delta G = 2RTV_H [c_H ln \frac{c_{H(1+\varphi)}}{c_H + \varphi c_L} + \varphi c_L ln \frac{c_{L(1+\varphi)}}{c_H + \varphi c_L}]$$
(8)

where ΔG is the free energy (J), V the volume (m³), and $\varphi = V_L/V_H$. H refers to the high concentration solution and L to the low concentration solution. When the hybrid device arrives to steady-state under solar irradiation, steam generates on the light absorber with a rate of v (m³ (m⁻² s⁻¹)), the theoretical power density of the formed salinity P (W m⁻²) can be expressed as:

$$P = \frac{\Delta G v}{V_H} \tag{9}$$

When φ is large enough, the value of ΔG will reach to a limiting value for a certain $V_{\rm H}$. Thus, we can calculate the efficiency of salinity power from solar energy and generated electricity form salinity gradient power.

3. Supplementary Figures



Figure S1. Characterization of the CNT modified filter paper. (a, b) SEM images of the CNT modified filter paper and (c) its photograph. (d) Contact angle (CA) of a typical CNT paper, indicating the CNT modified filter paper is superhydrophilic. (e) Adsorption spectrum of CNT filter paper. The inserted background is the solar irradiation spectrum.



Figure S2. Construction of the hybrid device. Two pieces of organic glass (thickness 1 mm) were cutting into required mould. Combing with homemade Ag/AgCl electrodes (thickness 0.3 mm), gaskets (thickness 0.5 mm), Nafion membrane (N117, thickness 0.18 mm), and the CNT filter paper (with a tail of 3 mm \times 1.5 cm), the device was constructed tightly by screws.



Figure S3. Experimental setup when measuring photothermal performance. Because the main components are plastic, the device can float directly on seawater. A layer of aluminum foil was pasted on the surface of the device with only the CNT paper area $(1 \text{ cm} \times 1 \text{ cm})$ exposing to sunlight during the solar desalination experiments, avoiding interfere of sunlight absorption around the CNT filter paper to the experimental results. Scale bars are 1 cm in both.



Figure S4. SEM image of the homemade Ag/AgCl electrode. The electrode shows a porous structure. Scale bar is 100 μm.



Figure S5. Sodium ion selective performance of Nafion membrane. (a) Schematic illustration of the potential difference measured across given salinity gradient. (b) Current-voltage curves of Nafion membrane in 6 M | 0.6 M NaCl gradient using Ag/AgCl electrode.



Figure S6. Temperature effect to the performance of Nafion membrane. Currentvoltage curves of Nafion membrane in 6 M | 0.6 M NaCl gradient at different temperatures. The voltage shows a litter increase with the temperature, which may be affected by transference number of cations and ions activity coefficient under high temperature,^{8, 9} on the basis of Eq. 5. High temperature facilitates ion diffusion in Nafion membrane, thus promotes the current.



Figure S7. The output power of the hybrid device at different solar irradiations. At 1 and 2 kW m⁻² illumination, the stable maximum output power of the hybrid device reaches 0.5 and 1.1 W m⁻², respectively.



Figure S8. The effect of membrane thickness on the performance of the device. (a) The open-circuit voltage of the device under one solar irradiation. (b) Current-voltage curves of the device under one solar irradiation. The results show that, with the decrease of the thickness, the output voltage will decrease a little because of the reduced effective concentration difference, but the current increases because of the reduced resistance. The output power increases from ~ 0.5 to ~ 0.55 W m⁻².



Figure S9. The electricity output of the device with different tail width under one solar irradiation. (a) The open-circuit voltage of the device. (b) Current-voltage curves and (c) output power of the hybrid device. Using 0.5 mm width tail, the device maximum power increased to 1 W m⁻² under one solar irradiation, which is comparable to the device with 3 mm width tail under two solar irradiation. (d) The evaporation induced mass loss of water for the device with 0.5 mm width tail. Inset shows the IR thermal images of the surface temperature of the CNT filter paper under solar irradiation.



Figure S10. The experiment setup for measuring the water weight change rate under natural solar irradiation. The device was covered by a layer of insulating foam except the CNT paper area.



Figure S11. A typical current-voltage curve of the large-scale hybrid device in 6 M | **0.6 M NaCl gradient.** An open-circuit voltage of 100 mV and a short-circuit current of 300 mA was obtained, generating a maximum output power of 7.5 mW.



Figure S12. The temperature and relative humidity around the experiment setup from 9:00 to 15:00 on July 30, 2017. The ambient temperature is around \sim 34 °C and relative humidity is ranging from \sim 30% RH to \sim 60% RH.

4. Supplementary References

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