Supporting Information

N-doped carbon@Cu core-shell nanostructure with nearly full solar spectrum absorption and enhanced solar evaporation efficiency

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1 Characterizations

The structure and morphology of the samples were measured using X-ray diffractor (XRD, Holland Panalytical PRO PW3040/60) with Cu Kα radiation (30 kV, 25 mA), Raman spectrometer (HARIBOR, Renishaw inVia), field-emission scanning electron microscope (FESEM, Hitachi S-4800) and transmission electron microscope (TEM, JEM-2100F). X-ray photoelectron spectroscopy (XPS, Escalab 250Xi photoelectron spectrometer) was used to investigate the composition. The ion concentration was measured by inductively coupled plasma optical emission spectrometer (ICP-OES, Optima 8300). The light absorption spectra of the samples were measured using a UV-Vis-NIR spectrophotometer (UV-3600, Shimadzu).

2 Solar steam generation experiments

The solar steam generation was measured in a 25 ml beaker, which was placed on the electronic balance (Sartorius, BSA224S) to record the mass change of water. 15 ml distilled water or simulated seawater was filled in the beaker. The membrane was placed on the foam wrapped by the air-laid paper. Then, the beaker was exposed to the simulated solar light irradiation. The 500 W Xenon lamp equipped with the standard AM 1.5 G optical filter was used to simulate the solar light. The light intensity was measured by the optical power meter (CEL-NP2000-2). At given time intervals, the water weight loss was recorded. The surface temperature of membrane was measured using an infrared camera (FLTR E95). The simulated seawater was prepared by dissolving 6.684 g NaCl, 0.050 g $NaHCO_3$, 0.873 g Na_2SO_4, 0.181 g KCl, 1.213 g $MgCl_2 \cdot 6\ H_2O$, 0.813 g $MgSO_4$ and 0.286 g $CaCl_2$ in 250 mL distilled water. 3.5 wt% NaCl solution was used for the cycling test. The cycling test for solar steam generation was carried out for four days. After each day, the membrane was washed to remove the crystalline salt for the next use. In the solar desalination section, the height of the evaporator was 4 cm.

The solar evaporation efficiency (η, %) was calculated using the following equation：

$$\eta = \frac{\dot{m}\Delta H}{C_{opt}P} \tag{S1}$$

where $\dot{m}$ is the evaporation rate (kg m^{-2} h^{-1}) $(\dot{m} = \dot{m}_{Light} - \dot{m}_{dark})$, $\dot{m}_{Light}$ and $\dot{m}_{dark}$ are the solar-to-vapor evaporation rate under the sunlight and dark conditions, respectively. C_{opt} is the optical concentration. P denotes the incident solar power (1 kW m^{-2}). $\Delta H = (H_V + Q)$ is the liquid-vapor phase change enthalpy. H_V is the phase-change enthalpy ($H_V = 1.91846 \times 10^6[T/(T - 33.91)]_2$ J kg^{-1}), and $Q = c(T - T_1)$ is the sensible heat of water. T is the surface temperature of solar evaporators, T_1 is the initial temperature of the water, and *c* is the specific heat of water (4.2 J g^{-1} K^{-1}). In this work, only the phase-change enthalpy is considered when calculating the evaporation efficiency.

Fig. S1 Digital photograph of the steam generated under four Sun illumination.

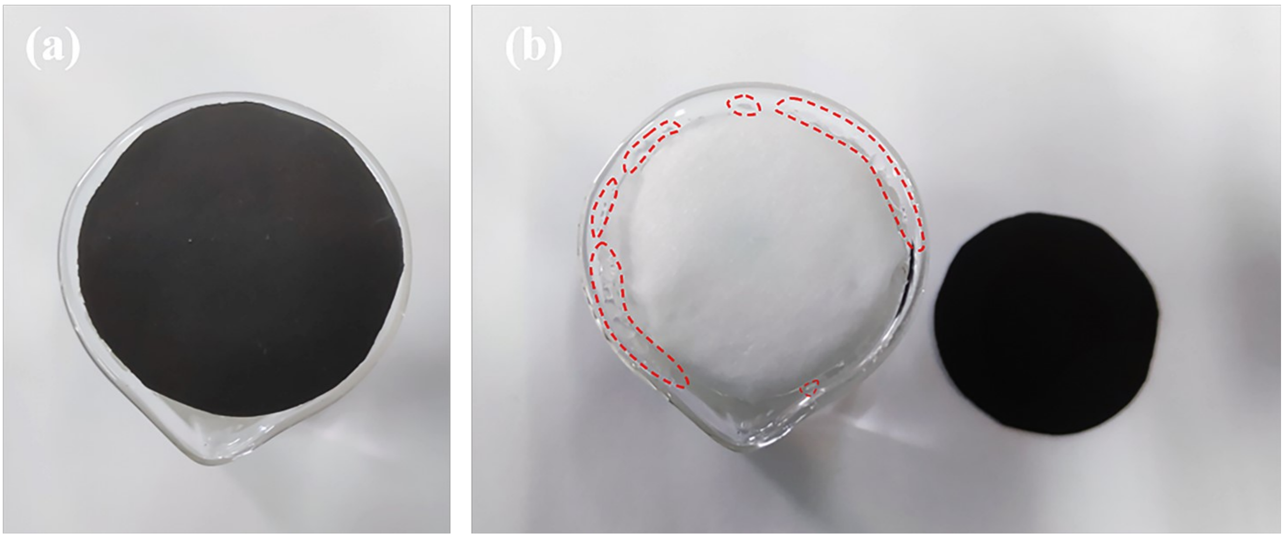

Fig. S2 Digital photograph of an evaporator with a height of 0 cm after one Sun illumination, where the NC@Cu film directly touches the edge of the beaker.

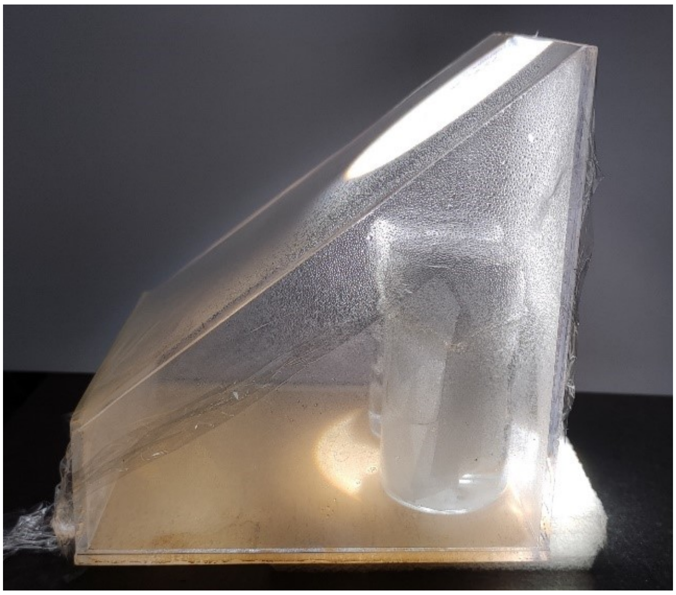

Fig. S3 Digital photograph of the homemade test setup for solar desalination.

Table S1 Evaporation rates of NC@Cu with different heights under dark.

Height(cm)	Evaporation rate (kg m^{-2} h^{-1})
0.5	0.265
2	0.3084
4	0.618
6	0.711

Table S2 Performance comparison of photothermal materials under simulated solar illumination

Photothermal materials	**Structure**	**Evaporation rate ($kg\ m^{-2}\ h^{-1}$)**	**Evaporation Efficiency (%)**	**Solar intensity ($kW\ m^{-2}$)**	**Refs**
Cu nanodot-embedded N-doped graphene	2D	1.29	82%	1	[S1]
Cu−Au core−shell NPs	2D	1.02	66%	1	[S2]
Cotton-CuS-agarose aerogel	3D	1.63	94.9%	1	[S3]
Reduced graphene oxide and rice straw fiber-based cylinder aerogel	3D	2.25	88.9%	1	[S4]
$CB/Al_2O_3/Cu$ foam	2D	1.31	79.8%	1	[S5]
Cu_3BiS_3/MXenes	3D	1.32	91.9%	1	[S6]
Cu/CuO foam	2.5D	4.1	-	1	[S7]
Ternary metallic sulfide (Ni-Co-Cu-S)	3D	2.48	99%	1	[S8]
NC@Cu	3D	2.76	137.1%	1	This work

Table S3 Concentrations of four major ions in the original simulated seawater and the desalinated water measured by ICP-OES.

Ions	Na^+ (mg L^{-1})	Mg^{2+} (mg L^{-1})	K^+ (mg L^{-1})	Ca^{2+} (mg L^{-1})
Simulated seawater	11918	1170	400	466
Desalinated water	17.906	1.497	1.612	1.662

Analysis of heat loss

(1) Radiation loss

The radiation heat loss can be calculated based on Stefan-Boltzmann equation.

$$\phi = \varepsilon A_1\sigma\left(T_1^4 - T^4\right) + \varepsilon A_2\sigma\left(T_2^4 - T^4\right) \quad \text{(S2)}$$

where ϕ (W m^{-2}) represents the radiation heat flux, ε is the emissivity of absorber which is assumed as 0.95 in the work, A_1 is the top surface area (8.55 cm^2), A_2 is the side surface area, σ is the Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}), T_1 is the average temperature of the absorber surface, T is the ambient temperature (296.78 K), and T_2 is the average temperature of the side surface.

(2) Convection loss:

The convection heat loss was calculated according to Newton' law of cooling:

$$Q = hA\left(T_1 - T\right) + hA\left(T_2 - T\right) \quad \text{(S3)}$$

where Q (W m^{-2}) denotes the convection heat flux, and h is the convection heat transfer coefficient supposed as 5 W m^{-2} K^{-1}.

(3) Conduction loss:

In this work, for the evaporator with the cold side surface ranging from 0.5 to 2.0 cm, the energy exchange between the bulk water and evaporation side is almost negligible, so it is assumed to be 0 W in this work.

According to the above equation, for the 0.5 cm height evaporator, A_1 is the top surface area (8.55 cm^2), A_2 is the side surface area (5.181 cm^2). Based on the above analysis, for the 0.5 cm height evaporator, the radiation loss from the top evaporation surface was 0.0751 W, while radiation loss of the side surface was estimated to be 0.0156 W. The convection loss from the top evaporation surface was 0.0620 W, while convection loss of the side surface was estimated to be 0.0135 W. Thus, the total energy loss was 0.1662 W.

According to the above equation, for the 6 cm height evaporator, A_1 is the top surface area (8.55 cm^2), A_2 is the side surface area (62.172 cm^2). For the 6 cm height evaporator, the radiation loss from the top evaporation surface was 0.0840 W, while radiation loss of the side surface was estimated to be -0.1806 W. The convection loss from the top evaporation surface was 0.0688 W, while radiation loss of the side surface was estimated to be -0.1648 W. Thus, the total energy loss was -0.1925 W.

Reference

S1. J. Xu, F. Xu, M. Qian, Z. Li, P. Sun, Z. Hong and F. Huang, *Nano Energy*, 2018, **53**, 425-431.

S2. Y. Wang, Q. Zhang, Y. Wang, L. V. Besteiro, Y. Liu, H. Tan, Z. M. Wang, A. O. Govorov, J. Z. Zhang, J. K. Cooper, J. Zhao, G. Chen, M. Chaker and D. Ma, *Chem. Mater.*, 2021, **33**, 695-705.

S3. X. Wu, M. E. Robson, J. L. Phelps, J. S. Tan, B. Shao, G. Owens and H. L. Xu, *Nano Energy*, 2019, **56**, 708-715.

S4. D. P. Storer, J. L. Phelps, X. Wu, G. Owens, N. I. Khan and H. Xu, *ACS Appl. Mater. Interfaces*, 2020, **12**, 15279-15287.

S5. N. Xu, J. L. Li, Y. Wang, C. Fang, X. Q. Li, Y. X. Wang, L. Zhou, B. Zhu, Z. Wu, S. N. Zhu and J. Zhu, *Sci. Adv.*, 2019, **5**, eaaw7013.

S6. Z. Wang, K. Yu, S. Gong, H. Mao, R. Huang and Z. Zhu, *ACS Appl. Mater. Interfaces*, 2021, **13**, 16246-16258.

S7. X. J. Liu, Y. P. Tian, F. Q. Chen, A. Caratenuto, J. A. DeGiorgis, M. ELSonbaty, Y. S. Wan, R. Ahlgren and Y. Zheng, *Adv. Funct. Mater.*, 2021, **31**, 2100911.

S8. T. Zhu, Z. He, Y. Ren, W. Zeng, J. Mao and L. Zhu, *Solar RRL*, 2021, **5**, 2100021.