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Supplementary information

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A 250-kilowatt system for co-production of hydrogen and fresh water from seawater

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Supplementary Information

250-kilowatt system for co-production of hydrogen and fresh water from seawater

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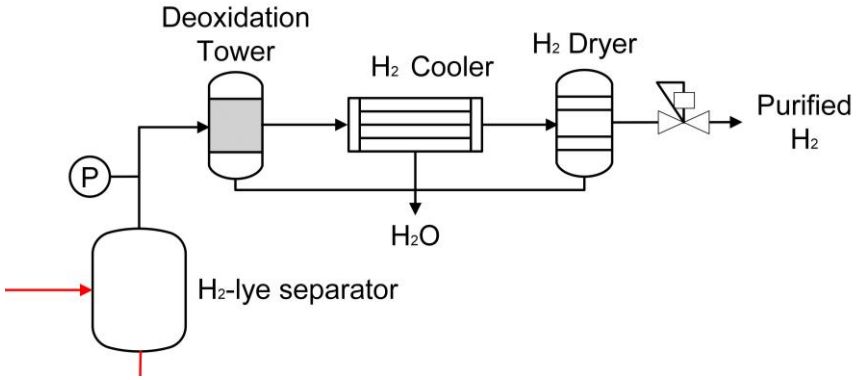


Supplementary Fig. 1. The hydrogen purification process of the STHW system. The separated H_2O is circulated to the fresh water tank for reuse in the electrolyzer.

Supplementary Table 1. The chemical compositions and corrosion resistance properties of 2205 standard duplex stainless steel for heat exchanger[1].

Description	Value
Steel grade	2205
ASTM	S32205
C content	0.02%
Cr content	22%
Ni content	5.7%
Mo content	3.1%
N content	0.17%
Pitting resistance equivalent number (PREN)[a]	35
Critical pitting temperatures (CPT)[b]	50 °C

[a] PREN = 1 × %Cr + 3.3 × %Mo + 16 × %N.

[b] Critical pitting temperatures according to ASTM G 150.

***Note*:** In the design of the waste heat recovery heat exchanger for the STHW system, we employed 2205 duplex stainless steel as the heat transfer material to balance the resistance to seawater corrosion and economy. Its PREN value is 35, thus making it suitable for environments requiring resistance to seawater corrosion. Furthermore, the actual seawater temperature in our reaction environment is below 50 °C, which is lower than the material's critical pitting temperature. Therefore, 2205 duplex stainless steel can meet the seawater corrosion resistance performance requirements of our pilot-scale facility. Concurrently, to fulfill the demands for long-term safe and stable operation under seawater conditions, it may be considered to select 2207 super duplex stainless steel (S31254/S32750) with PREN > 40 as the heat exchanger material.

Supplementary Note 1. Design of heat exchanger for waste heat recovery

A multi-pass coiled pipe was adopted as a heat exchanger for waste heat recovery. The calculation of heat exchanger area is the key step of heat exchanger design. It needs to be determined comprehensively based on three parameters: waste heat output, heat transfer coefficient, and logarithmic mean temperature difference. The design process is as follows:

The theoretical heat exchanger area is calculated using Equation (S1):

$$A_{theo}(m^2) = \frac{Q_{WH}}{K \times \Delta T_m} \quad \text{(Equation S1)}$$

where Q_{WH} is the waste heat output from Equation (14), K is the overall heat transfer coefficient (W m^{-2} K^{-1}), and ΔT_m is the logarithmic mean temperature difference.

The overall heat transfer coefficient (K) is calculated using Equation (S2):

$$\frac{1}{K} = \frac{1}{h_h} + \frac{\delta}{\lambda} + \frac{1}{h_c} + R_f \quad \text{(Equation S2)}$$

where h_h is the heat transfer coefficient of the hot lye stream (W m^{-2} K^{-1}), h_c is the heat transfer coefficient of boiling seawater (W m^{-2} K^{-1}), δ is the thickness of the pipe wall (m), λ is the thermal conductivity of the pipe (W m^{-1} K^{-1}), and R_f is the fouling thermal resistance (m^2 K W^{-1}).

The logarithmic mean temperature difference is calculated using Equation (S3):

$$\Delta T_m = \frac{(T_{h,i} - T_c) - (T_{h,o} - T_c)}{\ln\left(\frac{T_{h,i} - T_c}{T_{h,o} - T_c}\right)} \times F \quad \text{(Equation S3)}$$

where $T_{h,i}$, $T_{h,o}$ are the hot lye stream temperatures at the inlet and outlet of the heat exchanger, respectively (°C), T_c is the seawater temperature at the heat exchanger of the evaporator (°C), and F is the correction factor for non-countercurrent heat transfer.

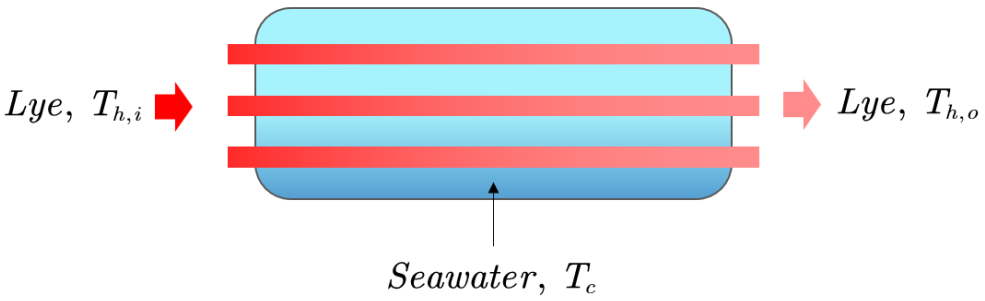
The practical heat exchanger area must be adjusted based on the operational fluctuation range and redundancy considerations. From an engineering application perspective, the equipment's operational range fluctuates between 30% and 120% of design capacity. Additionally, consideration must be given

to a 15% margin to account for fouling accumulation over the anticipated service life exceeding 10 years. Furthermore, a pneumatic diaphragm regulating valve is installed at the heat exchanger inlet to adjust the lye inflow. This valve is controlled by the temperature transmitter located at the electrolyzer outlet, maintaining the lye temperature within the range of 85 ± 1 °C to support efficient hydrogen production through water electrolysis. To ensure the regulating valve operates effectively within its reasonable control range, the heat exchange area is given a 20% margin. Consequently, the practical heat exchange area is calculated using Equation (S4):

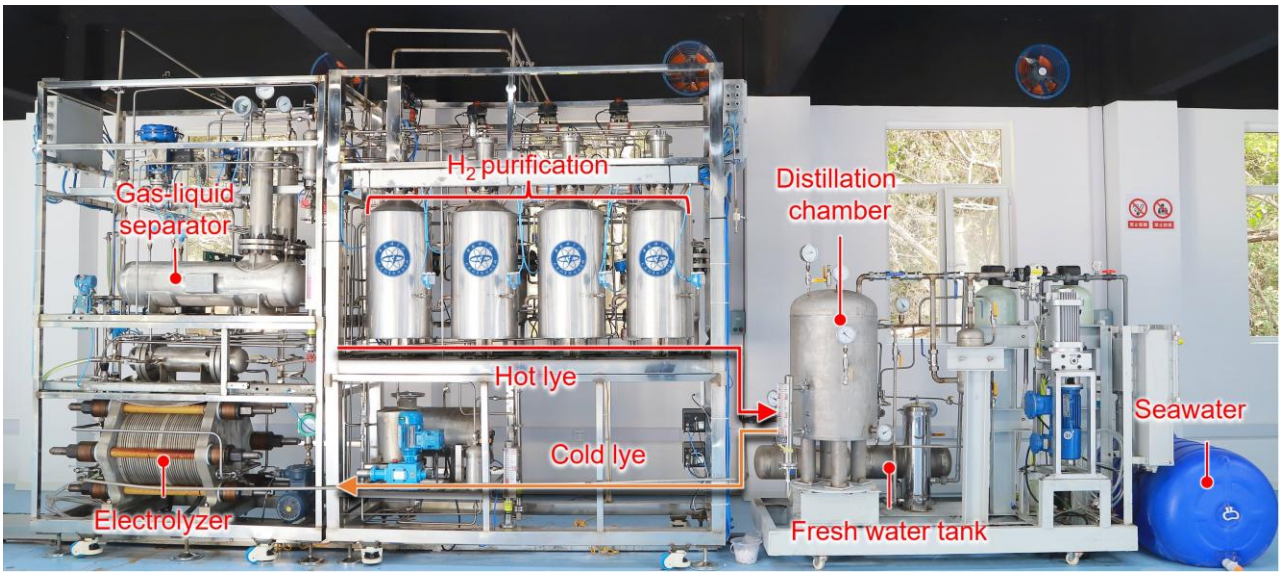
$$A_{practical}(m^2) = 1.2 \times 1.15 \times 1.2 \times A_{theo} \quad \text{(Equation S4)}$$

Supplementary Table 2. The selected heat exchanger design parameters for waste heat recovery of 20 kW system.

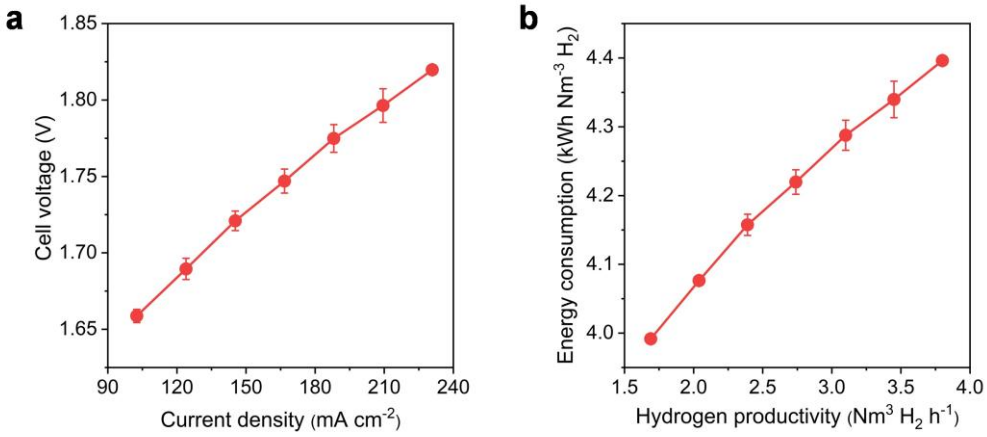
Name	Description	Value
$E_{electrolyzer}$	Energy consumption of the water electrolyzer	4.4 kWh Nm^{-3} H_2
$\dot{V}_{H_2}$	Volume flow rate of hydrogen produced	3.8 Nm^3 H_2 h^{-1}
Q	Heat load	3.344 kW
h_h	Heat transfer coefficient of hot lye stream	2200 W m^{-2} K^{-1}
h_c	Heat transfer coefficient of boiling seawater	8000 W m^{-2} K^{-1}
δ	Thickness of pipe wall	0.0015 m
λ	Thermal conductivity of pipe	19 W m^{-1} K^{-1}
R_f	Fouling thermal resistance	0.00008 m^2 K W^{-1}
K	Overall heat transfer coefficient	1354 W m^{-2} K^{-1}
$T_{h,i}$	Hot lye stream temperature at the inlet	85 °C
$T_{h,o}$	hot lye stream temperature at the outlet	60 °C
T_c	Seawater temperature	45 °C
F	Correction factor for non-countercurrent heat transfer	0.85
ΔT_m	Logarithmic mean temperature difference	21.67 K
A_{theo}	Theoretical heat exchanger area	0.114 m^2
$A_{practical}$	Practical heat exchanger area	0.189 m^2



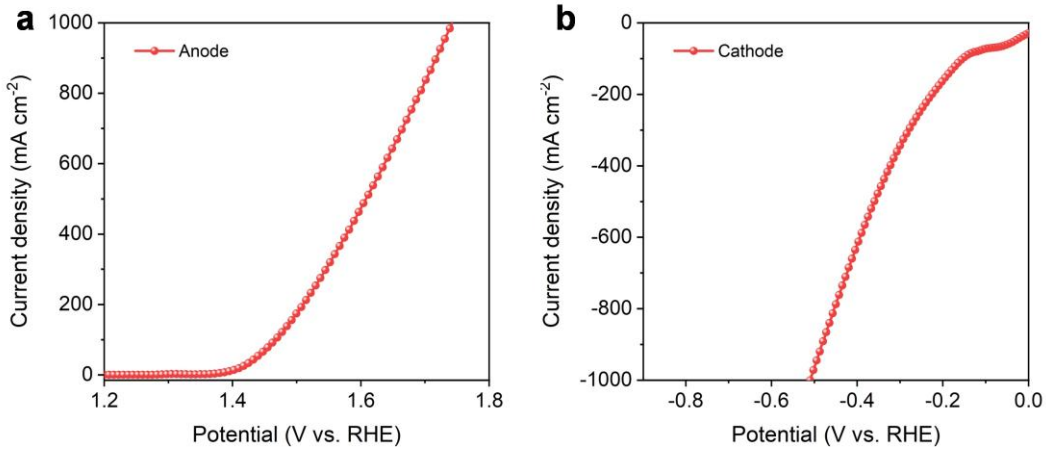
Supplementary Fig. 2. Configuration of the heat exchanger for waste heat recovery.



Supplementary Fig. 3. Photo of 20 kW equipment for co-production of hydrogen and fresh water from seawater.

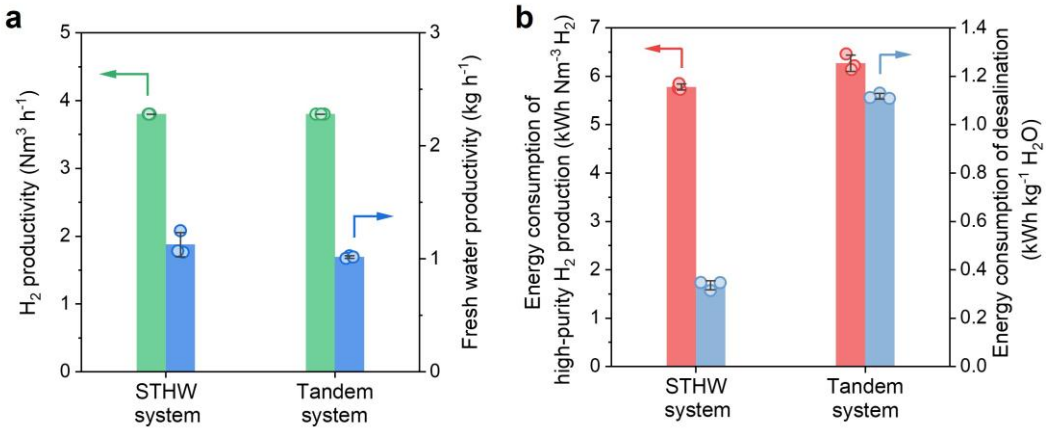


Supplementary Fig. 4. Electrochemical performance and energy consumption of the water electrolyzer in the 20 kW STHW system. (a) Polarization curve. (b) Energy consumption at varying hydrogen productivity. The Faradaic efficiency of the water electrolyzer is 99% for the water electrolyzer in our system, determined by design. Process conditions: the temperature, pressure, and electrolyte of water electrolysis are 85 °C, 1.2 MPa, and 30 wt% KOH, respectively. The data shown with error bars represent mean ± standard deviation (n = 3). ***Note*:** Based on the polarization curve of the water electrolyzer (Supplementary Fig. 4a), the electrolyzer energy consumption was calculated at varying hydrogen productivity (Supplementary Fig. 4b).



Supplementary Fig. 5. Electrode polarization curves of the 250 kW STHW system without *iR* compensation. (a) Anode polarization curve. (b) Cathode polarization curve. Reaction conditions: the temperature, pressure, and electrolyte of water electrolysis are 85 °C, 1 atm, and 30 wt% KOH, respectively. The counter electrode and reference electrode were a carbon rod and Hg/HgO electrode, respectively. ***Note*:** Using a three-electrode system, we measured the electrode potentials of the cathode and anode employed in the 20 kW STHW water electrolyzer. A customized Hg/HgO reference electrode (1 M KOH filling solution) was used, with a +1.008 V calibration for RHE conversion, determined using a Pt sheet electrode in a H_2-saturated 30 wt% KOH solution at 85 °C. The calculated equilibrium potential for the overall water electrolysis reaction under these conditions (85 °C, 1 atm, 30 wt% KOH) was 1.170 V[2-4]. This corresponds to equilibrium potentials of 0 V vs. RHE for the cathode, and 1.170 V vs. RHE for the anode, respectively.

The anode was Ni foam, exhibiting a potential of 1.510 V vs. RHE at a current density of 200 mA cm^{-2}, corresponding to an overpotential of 340 mV (Supplementary Fig. 5a). The cathode was NiMo foam, exhibiting a potential of -0.225 V vs. RHE at a current density of 200 mA cm^{-2}, corresponding to an overpotential of 225 mV (Supplementary Fig. 5b).



Supplementary Fig. 6. Comparison between the 20 kW STHW system and the tandem system of desalination followed by electrolysis, in terms of product productivity and energy consumption. (a) Productivity of H_2 and fresh water in both systems. (b) Energy consumption for high-purity hydrogen production and seawater desalination in both systems. Process conditions: the temperature, pressure, and electrolyte of water electrolysis are 85 °C, 1.2 MPa, and 30 wt.% KOH, respectively. The hydrogen productivity is 3.8 $Nm^3\ h^{-1}$. The temperature for the tower of waste heat recovery and distillation is around 44 °C. The data shown with error bars represent the mean ± standard deviation (n = 3) with individual data points overlaid on the bars.***Note*:** At a hydrogen productivity of 3.8 $Nm^3\ h^{-1}$ under optimum low-temperature distillation conditions, the tandem system generated fresh water at 1.0 kg h^{-1}, comparable to 1.1 kg h^{-1} of the STHW system (Supplementary Fig. 6a). In the STHW system, energy required for water vaporization is entirely supplied by waste heat from the water electrolyzer, resulting in a desalination energy consumption of 0.34 kWh kg^{-1} H_2O, which is significantly lower than 1.12 kWh kg^{-1} H_2O of the tandem system (Supplementary Fig. 6b). Additionally, the STHW system avoids energy consumption for waste heat removal via water-cooled condensers, while its high-purity hydrogen production requires 0.50 kWh Nm^{-3} H_2 less energy than the tandem system.

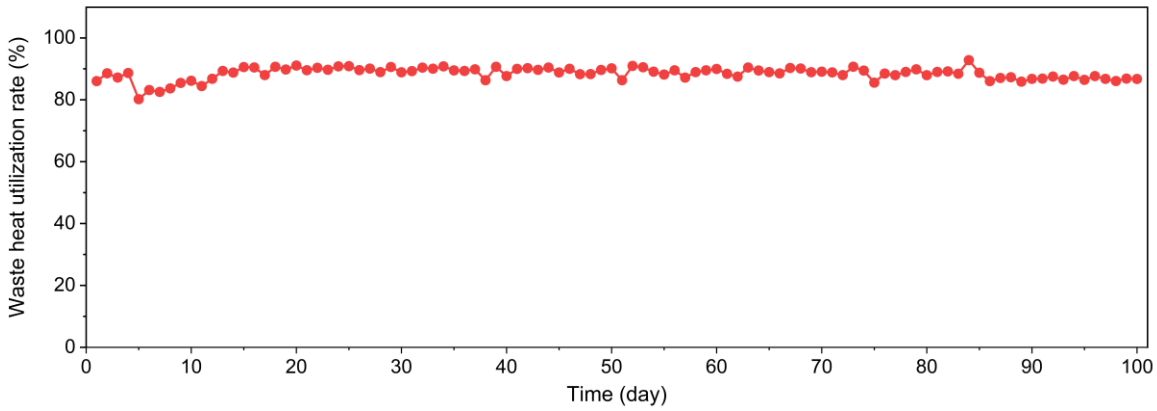
Supplementary Table 3. Productivity and energy consumption in the 20 kW STHW system and tandem VD-AWE system.

System	STHW system	VD-AWE tandem system
H_2 Productivity ($Nm^3\ h^{-1}$)	3.8	3.8
Fresh water productivity ($kg\ h^{-1}$)	1.0	1.1
Energy consumption of high-purity hydrogen production ($kWh\ h^{-1}$)	21.95	23.83
Energy consumption of high-purity hydrogen production ($kWh\ Nm^{-3}\ H_2$)	5.78	6.27
Energy consumption of desalination ($kWh\ h^{-1}$)	1.47	4.43
Energy consumption of desalination ($kWh\ kg^{-1}\ H_2O$)	0.34	1.12
Energy consumption of desalination relative to H_2 production ($kWh\ Nm^{-3}\ H_2$) [a]	0.37	1.19
Total system energy consumption ($kWh\ Nm^{-3}\ H_2$) [b]	6.14	7.46

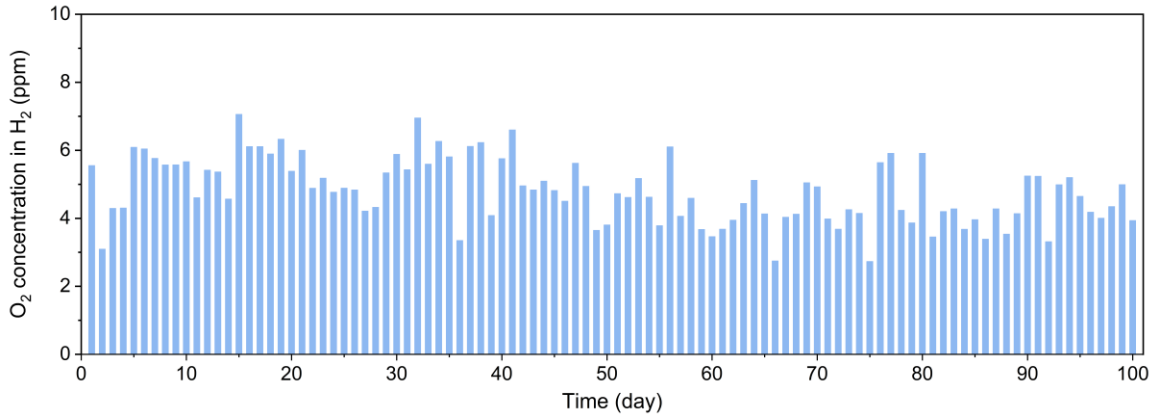
[a] The energy consumption of desalination relative to H_2 production is calculated as follows: Energy consumption of desalination relative to H_2 production ($kWh\ Nm^{-3}\ H_2$) = Energy consumption of desalination ($kWh\ h^{-1}$) / H_2 productivity ($Nm^3\ h^{-1}$).

[b] The total system energy consumption is calculated as follows: Total system energy consumption ($kWh\ Nm^{-3}\ H_2$) = Energy consumption of high-purity hydrogen production ($kWh\ Nm^{-3}\ H_2$) + Energy consumption of desalination relative to H_2 production ($kWh\ Nm^{-3}\ H_2$).

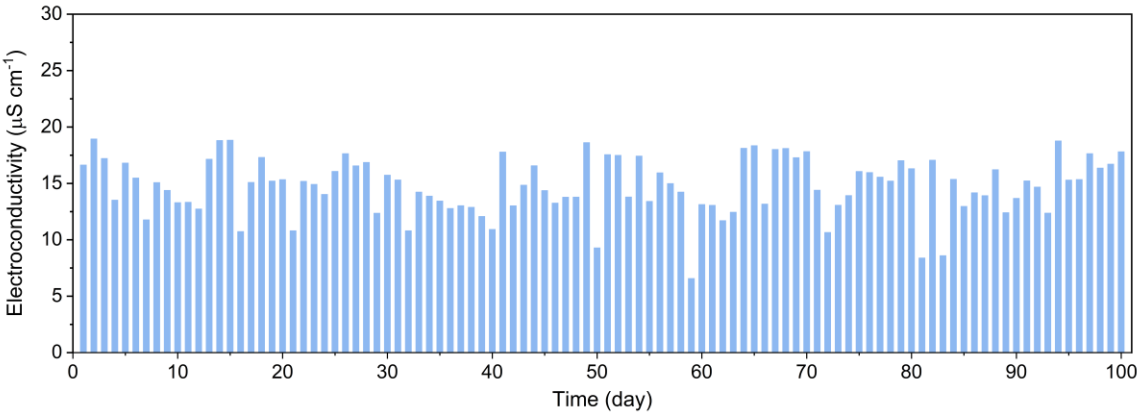
***Note*:** As shown in Supplementary Table 3, the STHW system achieves a lower system energy consumption of 6.14 $kWh\ Nm^{-3}\ H_2$, representing a 17.7% reduction compared with the 7.46 $kWh\ Nm^{-3}\ H_2$ of the tandem system.



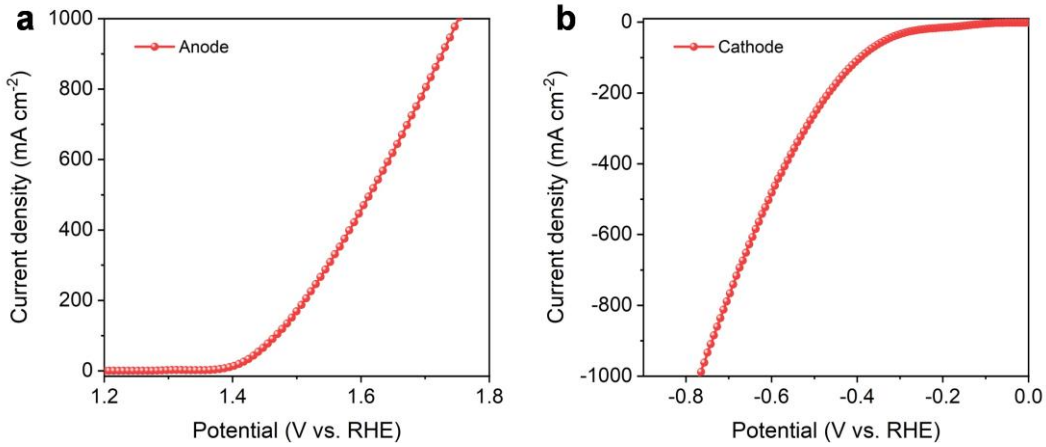
Supplementary Fig. 7. Waste heat utilization rate of the 20 kW STHW system during 100-day stability testing under daily start-stop with a 4-hour steady load. Process conditions: the temperature, pressure, and electrolyte of water electrolysis are 85 °C, 1.2 MPa, and 30 wt.% KOH, respectively. The hydrogen productivity is 3.8 Nm^3 h^{-1}. The evaporation temperature for the tower of waste heat recovery and distillation is around 44 °C.



Supplementary Fig. 8. O_2 concentration in H_2 produced by 20 kW system during 100-day stability testing under daily start-stop with a 4-hour steady load. Process conditions: the temperature, pressure, and electrolyte of water electrolysis are 85 °C, 1.2 MPa, and 30 wt.% KOH, respectively. The hydrogen productivity is 3.8 $Nm^3\ h^{-1}$. The evaporation temperature for the tower of waste heat recovery and distillation is around 44 °C.



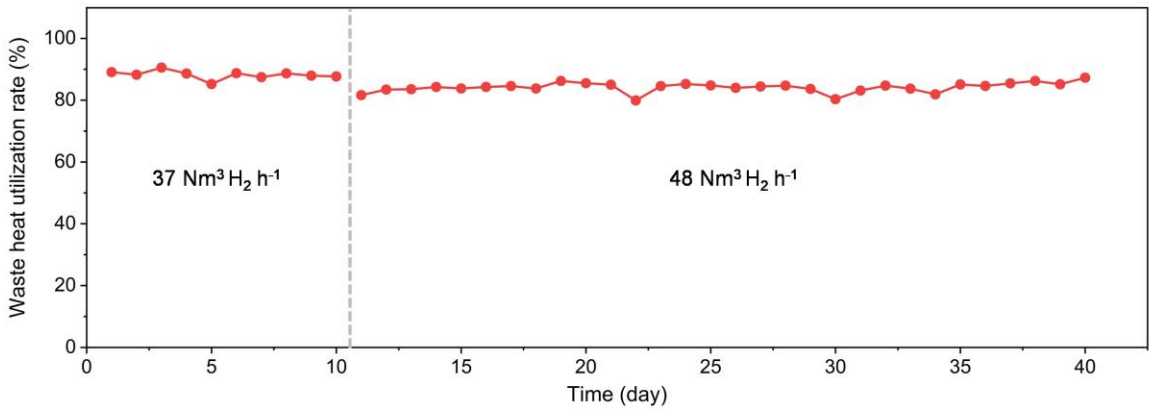
Supplementary Fig. 9. Electroconductivity of fresh water produced by 20 kW system during 100-day stability testing under daily start-stop with a 4-hour steady load. Process conditions: the temperature, pressure, and electrolyte of water electrolysis are 85 °C, 1.2 MPa, and 30 wt.% KOH, respectively. The hydrogen productivity is 3.8 Nm^3 h^{-1}. The evaporation temperature for the tower of waste heat recovery and distillation is around 44 °C.



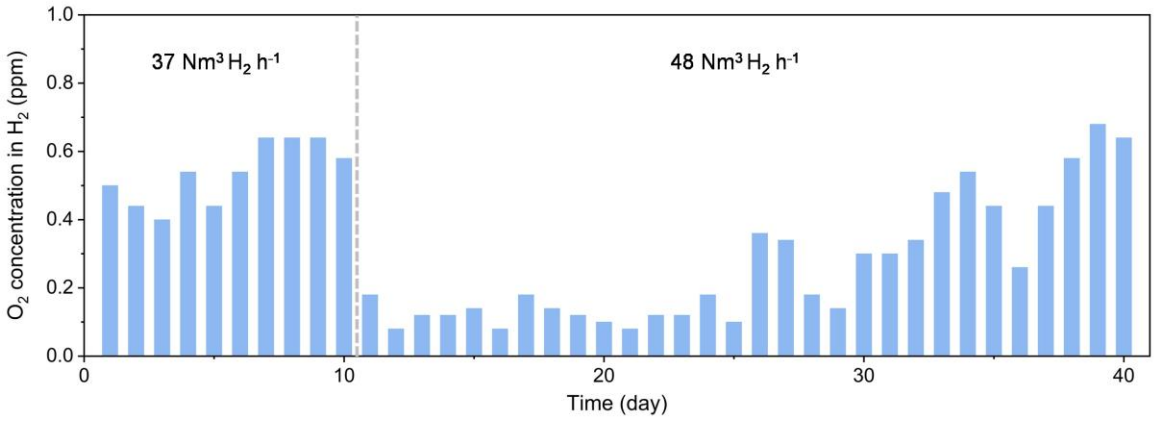
Supplementary Fig. 10. Electrode polarization curves of the 250 kW STHW system without *iR* compensation. (a) Anode polarization curve. (b) Cathode polarization curve. Reaction conditions: the temperature, pressure, and electrolyte of water electrolysis are 85 °C, 1 atm, and 30 wt% KOH, respectively. The counter electrode and reference electrode were a carbon rod and Hg/HgO electrode, respectively.

***Note*:** Using a three-electrode system, we measured the electrode potentials of the cathode and anode employed in the 250 kW STHW water electrolyzer. A customized Hg/HgO reference electrode (1 M KOH filling solution) was used, with a +1.008 V calibration for RHE conversion, determined using a Pt sheet electrode in a H_2-saturated 30 wt% KOH solution at 85 °C. The calculated equilibrium potential for the overall water electrolysis reaction under these conditions (85 °C, 1 atm, 30 wt% KOH) was 1.170 V[2-4]. This corresponds to equilibrium potentials of 0 V vs. RHE for the cathode, and 1.170 V vs. RHE for the anode, respectively.

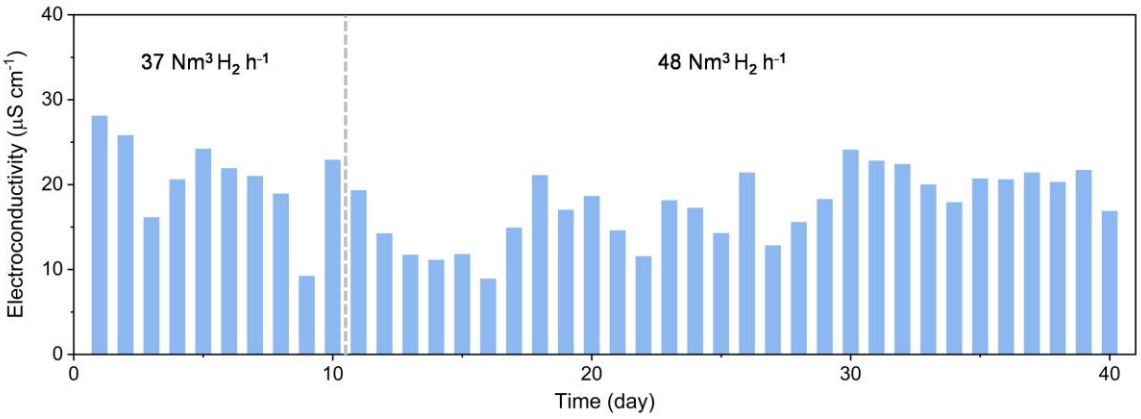
The anode was Ni foam, exhibiting a potential of 1.512 V vs. RHE at a current density of 200 mA cm^{-2}, corresponding to an overpotential of 342 mV (Supplementary Fig. 10a). The cathode was Ni foam, exhibiting a potential of -0.467 V vs. RHE at a current density of 200 mA cm^{-2}, corresponding to an overpotential of 467 mV (Supplementary Fig. 10b).



Supplementary Fig. 11. Waste heat utilization rate of 250 kW system during 40-day stability testing under daily start-stop with a 4-hour steady load. Process conditions: the temperature, pressure, and electrolyte of water electrolysis are 85 °C, 1.6 MPa, and 30 wt.% KOH, respectively. The hydrogen productivities are 37 Nm^3 h^{-1} for the first 10 days and 48 Nm^3 h^{-1} for the subsequent 30 days. The evaporation temperature for the tower of waste heat recovery and distillation is around 44 °C.



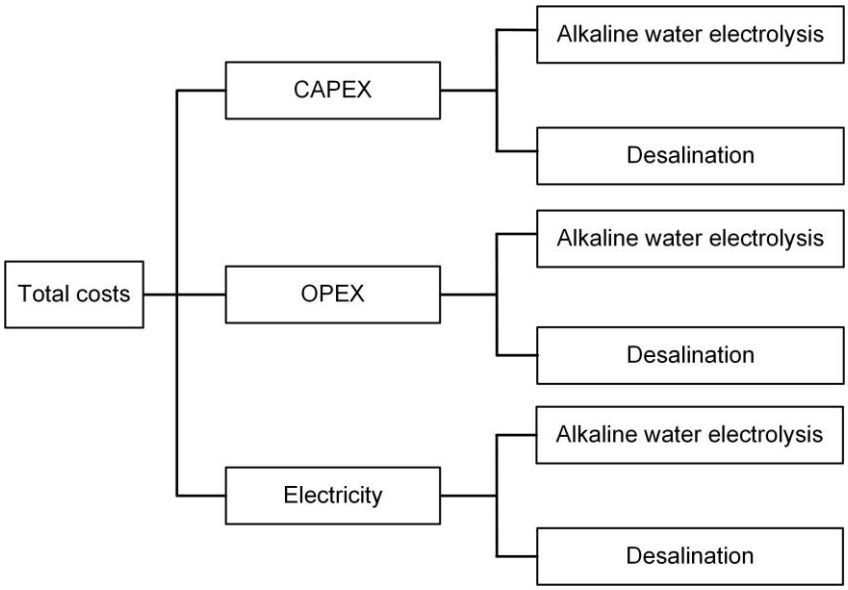
Supplementary Fig. 12. O_2 concentration in H_2 produced by 250 kW system during 40-day stability testing under daily start-stop with a 4-hour steady load. Process conditions: the temperature, pressure, and electrolyte of water electrolysis are 85 °C, 1.6 MPa, and 30 wt.% KOH, respectively. The hydrogen productivities are 37 $Nm^3\ h^{-1}$ for the first 10 days and 48 $Nm^3\ h^{-1}$ for the subsequent 30 days. The evaporation temperature for the tower of waste heat recovery and distillation is around 44 °C.



Supplementary Fig. 13. Electroconductivity of fresh water produced by 250 kW system during 40-day stability testing under daily start-stop with a 4-hour steady load. Process conditions: the temperature, pressure, and electrolyte of water electrolysis are 85 °C, 1.6 MPa, and 30 wt.% KOH, respectively. The hydrogen productivities are 37 Nm^3 h^{-1} for the first 10 days and 48 Nm^3 h^{-1} for the subsequent 30 days. The evaporation temperature for the tower of waste heat recovery and distillation is around 44 °C.

Supplementary Note 2. Techno-economic analysis

The techno-economic analysis model calculates both the plant-gate levelized cost and the levelized cost of hydrogen. We assess the alkaline water electrolysis and seawater desalination units independently. The total costs are primarily categorized into capital expenditure, fixed operation expenditure, and electricity costs, as shown in Supplementary Fig. 14. The lifetime of the plant is assumed to be 30 years. All currencies are in United States dollar unless otherwise stated.



Supplementary Fig. 14. Techno-economic analysis model for hydrogen production using the STHW system as well as traditional tandem systems. CAPEX refers to capital expenditure. OPEX refers to fixed operation expenditure, which does not include the energy cost.

The plant is assumed to have a production capacity of 50 tons d^{-1} for hydrogen and 9,285 tons d^{-1} for fresh water. Hydrogen production refers to a pressurized alkaline electrolysis facility as outlined in the Department of Energy's H2A Analysis. Plant lifetime is assumed to be 30 years. We initially assume a capacity factor (CF) of 97%. The spot price of hydrogen is taken to be \$3.90 kg^{-1} [5]. The spot price of oxygen is taken to be \$40 ton^{-1} [6]. The spot price of fresh water is taken to be \$1.45 ton^{-1} [7].

For the techno-economic analysis, the capital expenditure of the alkaline water electrolysis unit was set at \$1,055 kW^{-1}, corresponding to the 2020 benchmark for a 119 MW_AC electrolyzer system. The fixed operational expenditure was taken as \$7,758,000 yr^{-1}. The electrolyzer itself consumes 49.056 kWh kg^{-1} H_2.

For the balance of plant (BOP) electrical load, traditional tandem systems require 3.8 kWh kg^{-1} H_2, whereas the STHW system requires only 2.147 kWh kg^{-1} H_2. This reduction stems from the elimination of auxiliary cooling energy for the electrolyte (lye), which accounts for 43.5% of the total BOP electrical consumption in a conventional AWE system[8].

Regarding water use, the STHW system consumes 14.3 kg H_2O kg^{-1} H_2, covering both the water converted into H_2/O_2 and system losses[9]. In contrast, traditional tandem systems require 22.3 kg H_2O kg^{-1} H_2, which includes the water for hydrogen production plus additional losses from cooling-tower evaporation and cooling-medium replenishment[10].

The capital expenditure of the desalination unit in the STHW system was assumed to be \$1,600 ton^{-1} H_2O d^{-1}. The fixed operation expenditure includes chemical cost and labor cost. The specific chemical cost was taken to be \$0.04 ton^{-1} H_2O, and the specific labor cost was taken to be \$0.1 ton^{-1} H_2O[11]. The performance ratio (PR) was assumed to be 15.8 (kg distillate/2,326 kJ)[12]. The thermal energy consumption of distillation is calculated to be 40.9 kWh ton^{-1} H_2O, which is supplied by the waste heat of the water electrolyzer with a utilization rate of 85.1%. For auxiliary electrical consumption for desalination, the specific electrical consumption (SEC) is calculated using Equation (S5)[12]:

$$SEC[kWh\ m^{-3}] = a(PR)^{b} \quad \text{(Equation S5)}$$

where a is 7.6438, and b is -0.62. PR is 15.8. SEC equals to 1.38 kWh ton^{-1} H_2O.

For the reverse osmosis (RO) unit in the tandem system of seawater RO followed by alkaline water electrolysis (RO-AWE), the capital cost includes direct and indirect capital costs. The direct capital cost of the RO unit was assumed to be \$1,200 ton^{-1} H_2O d^{-1}, and the indirect capital cost of the RO unit was taken to be 27% of the direct capital cost [11]. The fixed operation expenditure includes chemical cost, labor cost, and the cost of RO membrane replacement. The specific chemical cost was taken to be \$0.04 ton^{-1} H_2O, and the specific labor cost was taken to be \$0.01 ton^{-1} H_2O[11]. The annual cost of RO membrane replacement is 8.3% of the direct capital cost of the RO unit[13] The electrical consumption of the RO unit was assumed to be 6.06 kWh ton^{-1} H_2O[12].

For the multi-effect distillation (MED) unit in the tandem system of seawater MED followed by alkaline water electrolysis (MED-AWE), the capital expenditure and fixed operation expenditure were taken identical to those of the desalination unit in the STHW system. The energy consumption of MED is 42.3 kWh ton^{-1} H_2O, consisting of 40.9 kWh ton^{-1} H_2O for thermal energy and 1.38 kWh ton^{-1} H_2O

for electrical energy[11,12].

The levelized cost of hydrogen ($LCOH$) is calculated using Equation (S6):

$$LCOH\ (\$\ kg^{-1}H_2) = \frac{TotCost - Oxygen\ revenue - Fresh\ water\ revenue}{Q_{H_2}} \quad \text{(Equation S6)}$$

where $TotCost$ is the total annual cost of the system over one year, and Q_{H_2} is the total quantity of hydrogen produced per year.

The total cost over one year is calculated using Equation (S7):

$$TotCost = AF \times CapEx + OpEx + Electricity \quad \text{(Equation S7)}$$

where $CapEx$ is the capital expenditure of the system. AF is the annualization factor. $OpEx$ is the fixed operation expenditure. $Electricity$ is the electrical cost.

The annualization factor is calculated using Equation (S8):

$$AF = \frac{r(1+r)^n}{((1+r)^n - 1)} \quad \text{(Equation S8)}$$

where the discount rate (r) is 5%. The project lifetime (n) is assumed to be 30 years, and all costs are normalized to the first year of the project [11,13].

The capital expenditure is calculated using Equation (S9):

$$CapEx = CapEx_{AWE} + CapEx_{Desal} = unitAWECost \times PowerE + wUnitCost \times M_d \quad \text{(Equation S9)}$$

where $unitAWECost$ is the capital cost of the alkaline water electrolysis size unit cost. $PowerE$ is the electrolyzer power. $wUnitCost$ is the desalination size unit cost. M_d is the fresh water production capacity.

The fixed operation expenditure is calculated using Equation (S10):

$$OpEx = OpEx_{AWE} + OpEx_{Desal} \quad \text{(Equation S10)}$$

where $OpEx_{AWE}$ is the fixed operation expenditure of alkaline water electrolysis, and $OpEx_{Desal}$ is the operation expenditure of desalination.

For the desalination units in both the STHW and MED-AWE systems, the $OpEx_{Desal}$ is calculated using Equation (S11):

$$OpEx_{Desal} = SCC_{Desal} \times CF \times M_d \times 365 + SLC_{Desal} \times CF \times M_d \times 365 \quad \text{(Equation S11)}$$

where SCC_{Desal} is the specific chemical cost of the desalination unit in both the STHW and MED-AWE systems (\$0.025 m^{-3}), SLC_{Desal} is the specific labor cost of the desalination unit in both the STHW and MED-AWE systems (\$0.1 m^{-3}), M_d is the fresh water production capacity per day.

For the desalination unit in the RO-AWE system, the $OpEx_{Desal}$ is calculated using Equation (S12):

$$OpEx_{Desal} = SCC_{RO} \times CF \times M_d \times 365 + SLC_{RO} \times CF \times M_d \times 365 + \mathrm{Re}p_{mem} \text{(Equation S12)}$$

where SCC_{RO} is the specific chemical cost of the RO unit, SLC_{RO} is the specific labor cost of the RO unit. $\mathrm{Re}p_{mem}$ is the annual cost of replacement for the RO membrane.

The annual cost of replacement for the RO membrane is calculated using Equation (S13):

$$\mathrm{Re}p_{mem} = 8.3\% \times DCC_{RO} \quad \text{(Equation S13)}$$

where DCC_{RO} is the direct capital cost of the RO unit.

The electricity cost is calculated using Equation (S14):

$$Electricity = eSEC \times EP \times M_{H_2} \times CF \times 365 + wSEC \times EP \times M_d \times CF \times 365 \quad \text{(Equation S14)}$$

where $eSEC$ is the total electrical usage of alkaline water electrolysis. $eSEC$ is the total energy usage of desalination. EP is the electricity price. M_{H_2} is the hydrogen production per day (based on mass), and M_d is the fresh water production per day.

The oxygen revenue is calculated using Equation (S15):

$$Oxygen\ revenue = 8 \times M_{H_2} \times CF \times 365 \times Oxygen\ price \quad \text{(Equation S15)}$$

The fresh water revenue is calculated using Equation (S16):

$$Fresh\ water\ revenue = \left(M_d - 14.3 \times M_{H_2}\right) \times CF \times 365 \times Fresh\ water\ price \quad \text{(Equation S16)}$$

The total quantity of hydrogen produced per year is calculated using Equation (S17):

$$Q_{H_2} = M_{H_2} \times CF \times 365 \qquad \text{(Equation S17)}$$

Supplementary Table 4. Costs and revenues list of the plant of STHW system for hydrogen production from seawater. RO-AWE refers to tandem system of seawater reverse osmosis followed by alkaline water electrolysis. MED-AWE refers to tandem system of seawater multi-effect distillation followed by alkaline water electrolysis. BOP refers to the balance of plant for the AWE component.

Basic data of the STHW system			
Plant life (yr)	30	Annualization factor	0.065
Capital factor	97%	Waste heat utilization rate	85.1%
H_2 production capacity (ton d^{-1})	50	O_2 production capacity (ton d^{-1})	400
Fresh water production capacity (ton d^{-1})	9285		
Alkaline water electrolysis			
Electrolyzer power (MW_AC)	119	H_2 production capacity (ton d^{-1})	50
Fresh water consumption (kg H_2O kg^{-1} H_2)	14.3	Electrolyzer electrical usage (kWh kg^{-1})	49.056
BOP electrical usage (kWh kg^{-1})	2.148	Stack capital cost (\$k yr^{-1})	2,284
Mechanical BOP (\$k yr^{-1})	2,064	Electrical BOP (\$k yr^{-1})	1,339
Total indirect capital (\$k yr^{-1})	2,104	Fixed operation expenditure (\$k yr^{-1})	7,758
Seawater desalination			
Fresh water production capacity (ton d^{-1})	10,000	Total electrical usage (kWh m^{-3})	1.38
Capital cost (\$k yr^{-1})	1,041	Annual chemical cost (\$k yr^{-1})	88.5
Annual labor cost (\$k yr^{-1})	354.1		

Revenues			
	Productivity (ton yr^{-1})	Price (\$ ton^{-1})	Revenue (\$k yr^{-1})
H_2	17,702.5	3,900	69,040
O_2	141,620	40	5,665
Fresh water	3,287,354	1.45	4,776

Note: For the STHW system, the calculated standalone fresh water production cost is \$0.460 m^{-3} H_2O, which represents a water production cost of 0.3% of the electrolysis cost (\$2.41 kg^{-1} H_2).

Supplementary Table 5. Costs and revenues list of the plant of RO-AWE system for hydrogen production from seawater. RO-AWE refers to tandem system of seawater reverse osmosis followed by alkaline water electrolysis. BOP refers to the balance of plant for the AWE component.

Basic data of the RO-AWE system			
Plant life (yr)	30	Annualization factor	0.065
Capital factor	97%	H_2 production capacity (ton d^{-1})	50
O_2 production capacity (ton d^{-1})	400	Fresh water production capacity (ton d^{-1})	9285
Alkaline water electrolysis			
Electrolyzer power (MW_AC)	119	H_2 production capacity (ton d^{-1})	50
Fresh water consumption (kg H_2O kg^{-1} H_2)	22.3	Electrolyzer electrical usage (kWh kg^{-1})	49.056
BOP electrical usage (kWh kg^{-1})	3.8	Stack capital cost ($k yr^{-1})	2,284
Mechanical BOP ($k yr^{-1})	2,346	Electrical BOP ($k yr^{-1})	1,339
Total indirect capital ($k yr^{-1})	2,208	Fixed operation expenditure ($k yr^{-1})	7,758
Seawater desalination			
Fresh water production capacity (ton d^{-1})	10,088	Total electrical usage (kWh m^{-3})	6.06
Capital cost ($k yr^{-1})	1,031	Annual chemical cost ($k yr^{-1})	147.3
Annual labor cost ($k yr^{-1})	36.8	Membrane replace ($k yr^{-1})	1,036

Revenues			
	Productivity (ton yr^{-1})	Price ($ ton^{-1})	Revenue ($k yr^{-1})
H_2	17,702.5	3,900	69,040
O_2	141,620	40	5,665
Fresh water	3,287,354	1.45	4,776

Note: For the RO-AWE tandem system, the calculated standalone fresh water production cost is $0.793 m^{-3} H_2O, which represents a water production cost of 0.7% of the electrolysis cost ($2.49 kg^{-1} H_2).

Supplementary Table 6. Costs and revenues list of the plant of MED-AWE system for hydrogen production from seawater. MED-AWE refers to tandem system of seawater multi-effect distillation followed by alkaline water electrolysis. BOP refers to the balance of plant for the AWE component.

Basic data of the MED-AWE system			
Plant life (yr)	30	Annualization factor	0.065
Capital factor	97%	H_2 production capacity (ton d^{-1})	50
O_2 production capacity (ton d^{-1})	400	Fresh water production capacity (ton d^{-1})	9285
Alkaline water electrolysis			
Electrolyzer power (MW_AC)	119	H_2 production capacity (ton d^{-1})	50
Fresh water consumption (kg H_2O kg^{-1} H_2)	22.3	Electrolyzer electrical usage (kWh kg^{-1})	49.056
BOP electrical usage (kWh kg^{-1})	3.8	Stack capital cost (\$k yr^{-1})	2,284
Mechanical BOP (\$k yr^{-1})	2,346	Electrical BOP (\$k yr^{-1})	1,339
Total indirect capital (\$k yr^{-1})	2,208	Fixed operation expenditure (\$k yr^{-1})	7,758
Seawater desalination			
Fresh water production capacity (ton d^{-1})	10,088	Total electrical usage (kWh m^{-3})	42.27
Capital cost (\$k yr^{-1})	1,082	Annual chemical cost (\$k yr^{-1})	92.1
Annual labor cost (\$k yr^{-1})	368.2		

Revenues			
	Productivity (ton yr^{-1})	Price (\$ ton^{-1})	Revenue (\$k yr^{-1})
H_2	17,702.5	3,900	69,040
O_2	141,620	40	5,665
Fresh water	3,287,354	1.45	4,776

Note: For the MED-AWE tandem system, the calculated standalone fresh water production cost is \$1.687 m^{-3} H_2O, which represents a water production cost of 1.5% of the electrolysis cost (2.49 kWh Nm^{-3} H_2).

Supplementary Table 7. Energy consumption for seawater desalination and energy and water consumption for AWE via different routes.

Route	Desalination	AWE		Proportion[a]
	Energy consumption (kWh/m^3 H_2O)	Water consumption (m^3 H_2O/kg H_2)	Energy consumption (kWh/kg H_2)	
STHW	1.38	0.0143	51.20	0.04%
RO-AWE	6.06	0.0223	52.86	0.26%
MED-AWE	42.27	0.0223	52.86	1.78%

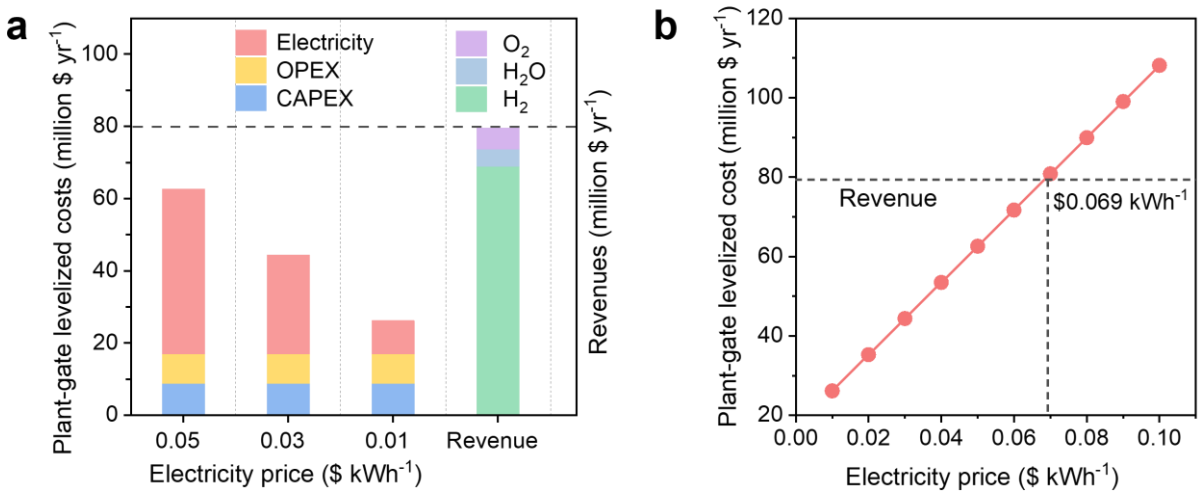
[a] The proportion of energy consumption attributable to seawater desalination within the overall AWE system is calculated as follows: Proportion (%) = (Energy consumption$_{desalination}$ × Water consumption$_{AWE}$) / Energy consumption$_{AWE}$.

Supplementary Table 8. Comparison of total system energy consumption for different systems.

System	Total system energy consumption (kWh d^{-1})[a]
STHW	2,496,740
RO-AWE	2,624,649
MED-AWE	2,989,976

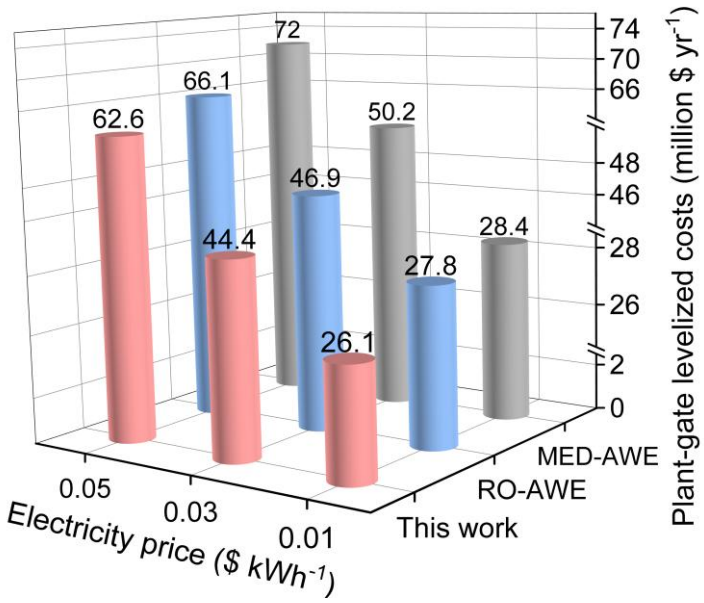
[a] The system energy consumption of plants is calculated as follows: System energy consumption (kWh d^{-1}) = (Electrolyzer electrical usage + BOP electrical usage) × H_2 production capacity × Capital factor + Total electrical usage of desalination × Fresh water production capacity × Capital factor.

Note: As shown in Supplementary Table 8, the STHW system achieves lower system energy consumption, representing reductions of approximately 5% and 16% relative to the RO-AWE and MED-AWE systems, respectively. The results were calculated using the following formula: Reduction (%) = (Energy consumption of RO-AWE or MED-AWE system − Energy consumption of STHW system) / Energy consumption of RO-AWE or MED-AWE system × 100%.



Supplementary Fig. 15. Cost breakdown and levelized cost of the STHW system under different electricity prices. (a) Breakdown of annual plant-gate levelized costs at different electricity prices compared with revenues. The costs include capital expenditure (CAPEX), operation expenditure (OPEX, which excludes energy costs) and electricity cost. The revenues include hydrogen, oxygen, and fresh water revenues. (b) Annual plant-gate levelized cost with varying electricity prices.

***Note*:** Under the electricity price of \$0.069 kWh^{-1}, the plant-gate levelized cost is equal to its revenue (Supplementary Fig. 15b).



Supplementary Fig. 16. Comparison of annual plant-gate levelized costs between the STHW system and traditional tandem systems. RO-AWE refers to the tandem system of seawater reverse osmosis followed by AWE. MED-AWE refers to the tandem system of seawater multi-effect distillation followed by AWE. The default capacity factor is set to 97% if not specified.

Supplementary Note 3. The consideration of water losses

Considering that the water in the gas product after separation is recirculated into the fresh water tank for reuse in the electrolyzer, the water loss in the gas is determined by measuring the dew point. The measured dew point of hydrogen is -2 °C, corresponding to the saturated pressure of water of 0.511 kPa. The measured dew point of oxygen is 2 °C, corresponding to the saturated pressure of water of 0.696 kPa.

The total water volume loss under standard conditions is calculated using Equation (S18):

$$\dot{V}_{FW,loss} = P_{H_2O/H_2}/P_0 \times \dot{V}_{H_2} + P_{H_2O/O_2}/P_0 \times \dot{V}_{O_2} \quad \text{(Equation S18)}$$

where P_{H_2O/H_2} is the saturated pressure of H_2O in H_2. P_{H_2O/O_2} is the saturated pressure of H_2O in O_2. P_0 is the standard atmospheric pressure, equal to 101.325 kPa. $\dot{V}_{H_2}$ is the hydrogen volume flow rate. $\dot{V}_{O_2}$ is the oxygen volume flow rate, equal to $0.5\dot{V}_{H_2}$.

The fresh water mass loss relative to H_2 productivity is calculated using Equation (S19):

$$\frac{\dot{m}_{FW,loss}}{\dot{m}_{H_2}} = \frac{MM_{H_2O}}{MM_{H_2}} \times \frac{\dot{V}_{FW,loss}}{\dot{V}_{H_2}} \quad \text{(Equation S19)}$$

where $\dot{m}_{H_2}$ is the hydrogen mass productivity. MM_{H_2O} is the molar mass of water (18.02 g mol^{-1}). MM_{H_2} is the molar mass of H_2 (2.01 g mol^{-1}).

The fresh water mass loss relative to the fresh water theoretical demand of the water electrolyzer is calculated using Equation (S20):

$$\frac{\dot{m}_{FW,loss}}{\dot{m}_{FW,demand}} = \frac{MM_{H_2O}}{MM_{H_2}} \times \frac{\dot{m}_{FW,loss}}{\dot{m}_{H_2}} \quad \text{(Equation S20)}$$

where $\dot{m}_{FW,\ demand}$ is the fresh water theoretical demand of the water electrolyzer.

Supplementary Table 9. Water losses in the gas product for water electrolyzer of 20 kW system.

Name	Description	Value
T_{dew,H_2}	Measured H_2 dew point	-2 °C
P_{H_2O/H_2}	Saturated vapor pressure of water in H_2	0.511 kPa
T_{dew,O_2}	Measured O_2 dew point	2 °C
P_{H_2O/O_2}	Saturated vapor pressure of water in O_2	0.696 kPa
P_0	Standard atmospheric pressure	101.325 kPa
$\frac{\dot{m}_{FW,loss}}{\dot{m}_{H_2}}$	Total fresh water loss relative to H_2 productivity	0.076 kg kg^{-1} H_2
$\frac{\dot{m}_{FW,loss}}{\dot{m}_{FW,demand}}$	Total fresh water loss relative to fresh water theoretical demand of electrolyzer	0.008 kg kg^{-1} H_2O

Note: The fresh water mass loss relative to fresh water theoretical demand of electrolyzer is 0.8%, which is neglected.

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