Supplemental information

Self-adaptive interfacial cooling for sustainable energy-water cogeneration in photovoltaics

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Supplementary Tables

Table S1 Parameters required for LCOE calculation.

Tech type	Component	Unit price	Unit price per m^2	Lifetime (year)	Manufacturing Cost
PV	PV panel [1]	0.306 \$/W	68.94 \$/m^2	12	0 \$/m^2
IEWC	PV panel [1]	0.306 \$/W	68.94 \$/m^2	12	0.05 \$/m^2
	Evaporator	0.312 \$/m^2	0.312 \$/m^2	1	
Spray cooling PV/T	PV panel [1]	0.306 \$/W	68.94 \$/m^2	12	0.818 \$/m^2
	Nozzle	0.682 \$/each	0.349 \$/m^2	1	
Flat plate PV/T [2]	PV panel [1]	0.306 \$/W	68.94 \$/m^2	12	3.13 \$/m^2
	Glass [3]	2.66 \$/m^2	2.66 \$/m^2	12	
Tube plate PV/T [4]	PV panel [1]	0.306 \$/W	68.94 \$/m^2	12	2.05 \$/m^2
	Copper plate [5]	8916.32 \$/MT	8.92 \$/m^2	12	

Table S2 Photovoltaic source initial characteristics [7].

Initial characteristic	Unit	Value
Greenhouse gas emissions	$kgCO_2$/(MWh/a)	52
	$kgCO_2$/MW	30368
Land use	m^2/(MWh/a)	19.23
	m^2/MW	11230.32
Dissipated water use	m^3/(MWh/a)	35
	m^3/MW	20440

Table S3 Resource saving result.

Yearly saving	Emission (tCO_2)	Land use (km^2)	Water use ($\times 10^9$ t)	Water use (Consider water production, $\times 10^9$ t)
2025	1821226.90	673.50	1.2258	1.2300
2026	1626182.93	601.37	1.0945	1.0998
2027	1451859.49	536.91	0.9772	0.9836
2028	1296070.22	479.30	0.8724	0.8802
2029	1156858.12	427.82	0.7787	0.7881
2030	1032471.62	381.82	0.6949	0.7064
2031	921343.09	340.72	0.6201	0.6338
2032	822069.70	304.01	0.5533	0.5696
2033	733396.10	271.22	0.4936	0.5129
2034	654199.05	241.93	0.4403	0.4630
2035	583473.58	215.77	0.3927	0.4192
2036	520320.60	192.42	0.3502	0.3810
2037	463935.80	171.57	0.3123	0.3478
2038	413599.74	152.95	0.2784	0.3191
2039	368668.93	136.34	0.2481	0.2945
2040	328567.84	121.51	0.2212	0.2735
2041	292781.80	108.27	0.1971	0.2559
2042	260850.59	96.46	0.1756	0.2412
2043	232362.71	85.93	0.1564	0.2292
2044	206950.26	76.53	0.1393	0.2194
2045	184284.33	68.15	0.1240	0.2117
2046	164070.95	60.67	0.1104	0.2056
2047	146047.31	54.01	0.0983	0.2009
2048	129978.59	48.07	0.0875	0.1948
2049	115654.91	42.77	0.0778	0.1890
2050	102888.73	38.05	0.0693	0.1842

Supplementary Figures

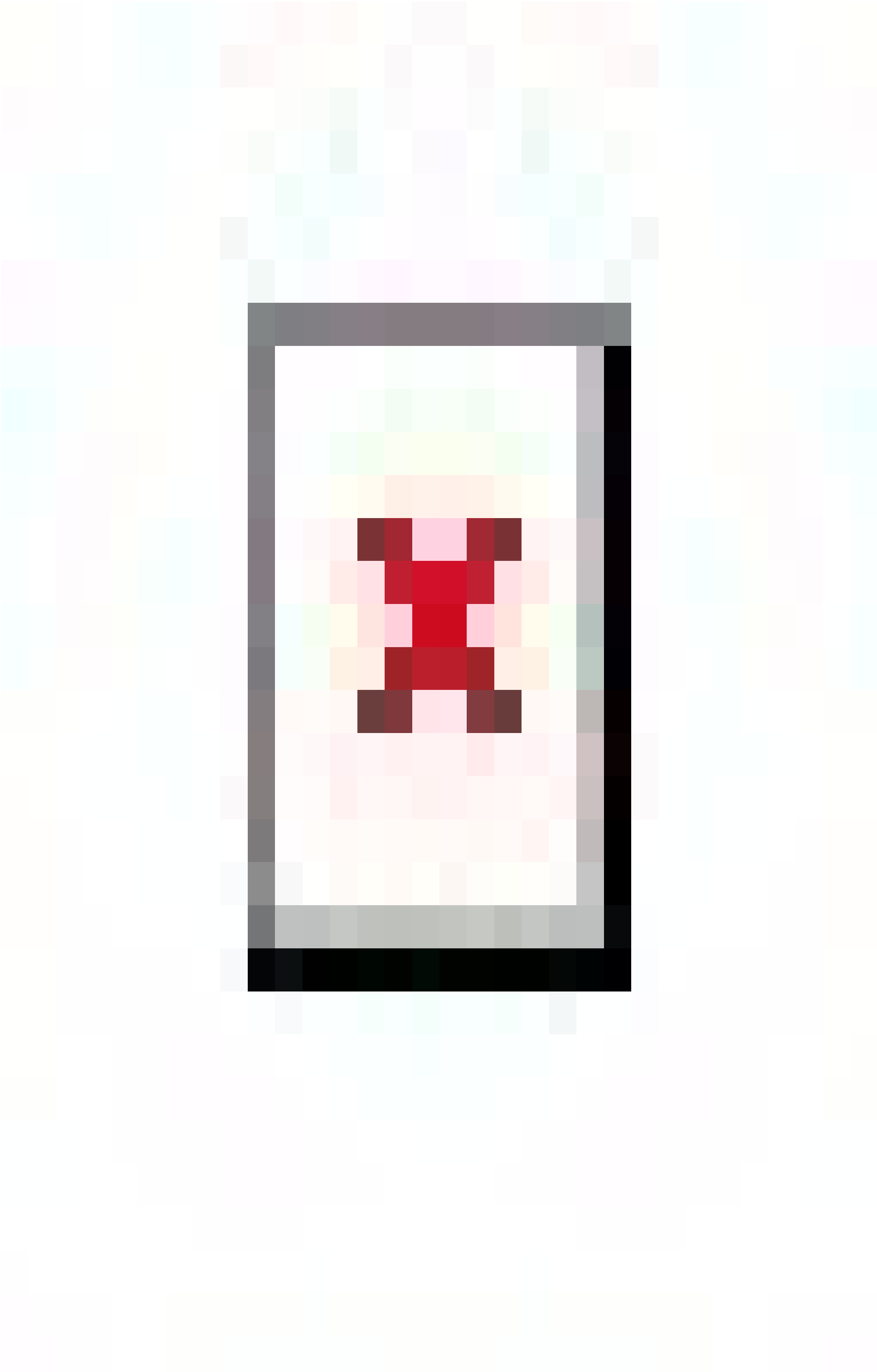

Fig. S1. ROL comparison of different cooling method (Discount ratio = 1%).

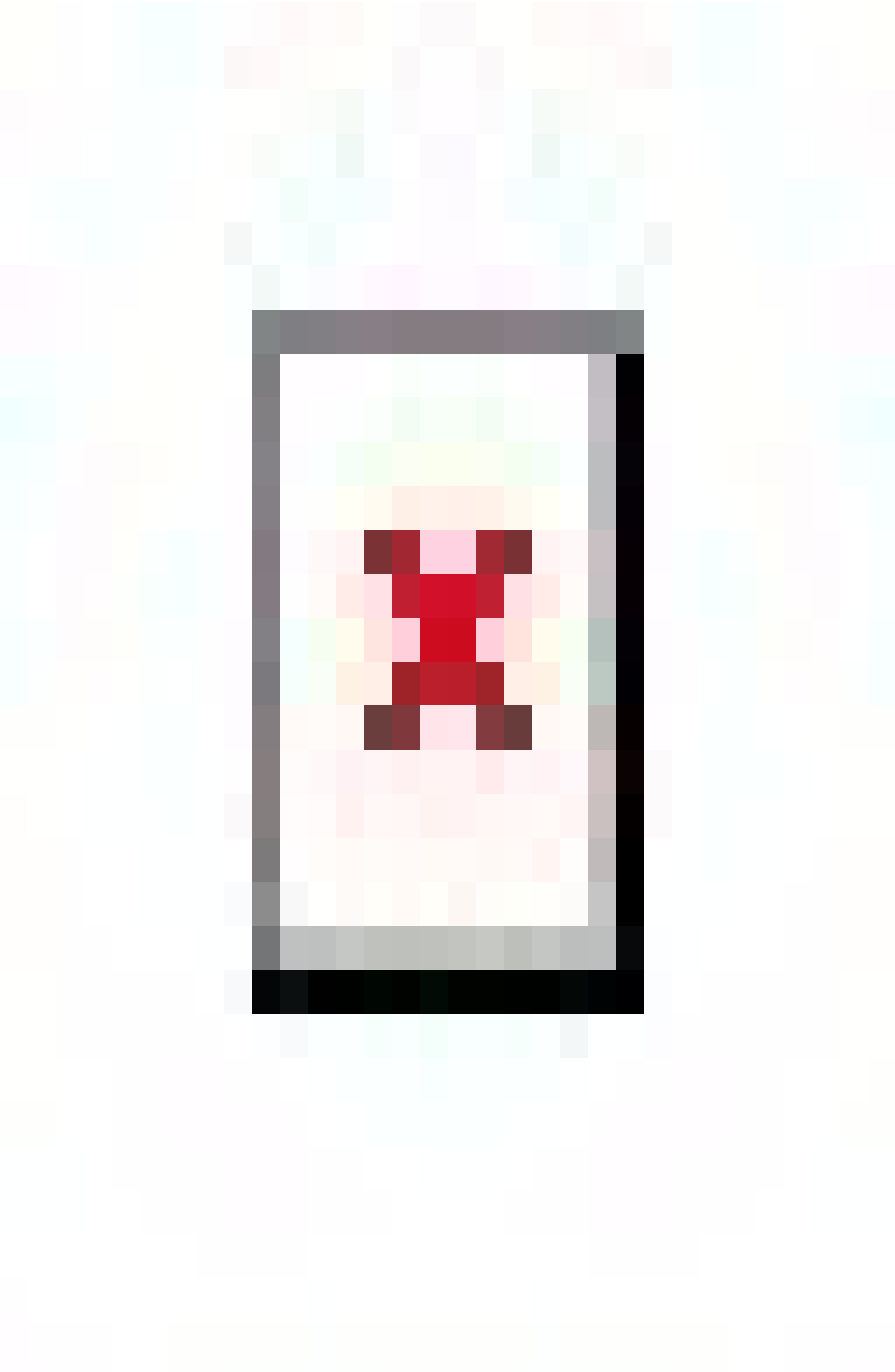

Fig. S2. ROL comparison of different cooling method (Discount ratio = 3%).

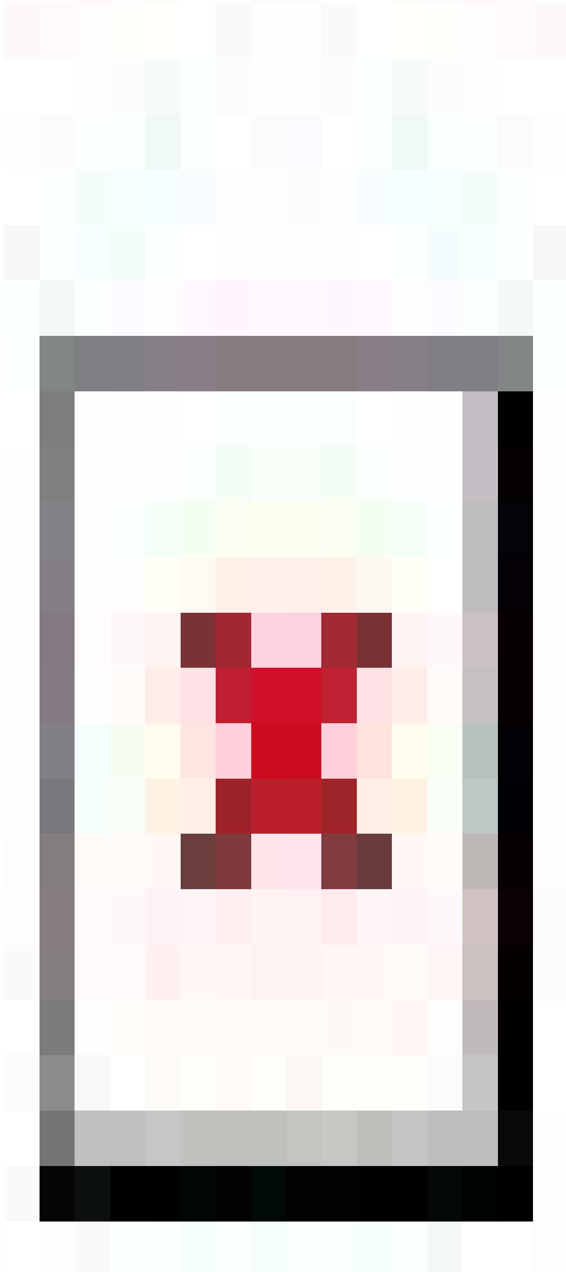

Fig. S3. ROL comparison of different cooling method (Discount ratio = 5%).

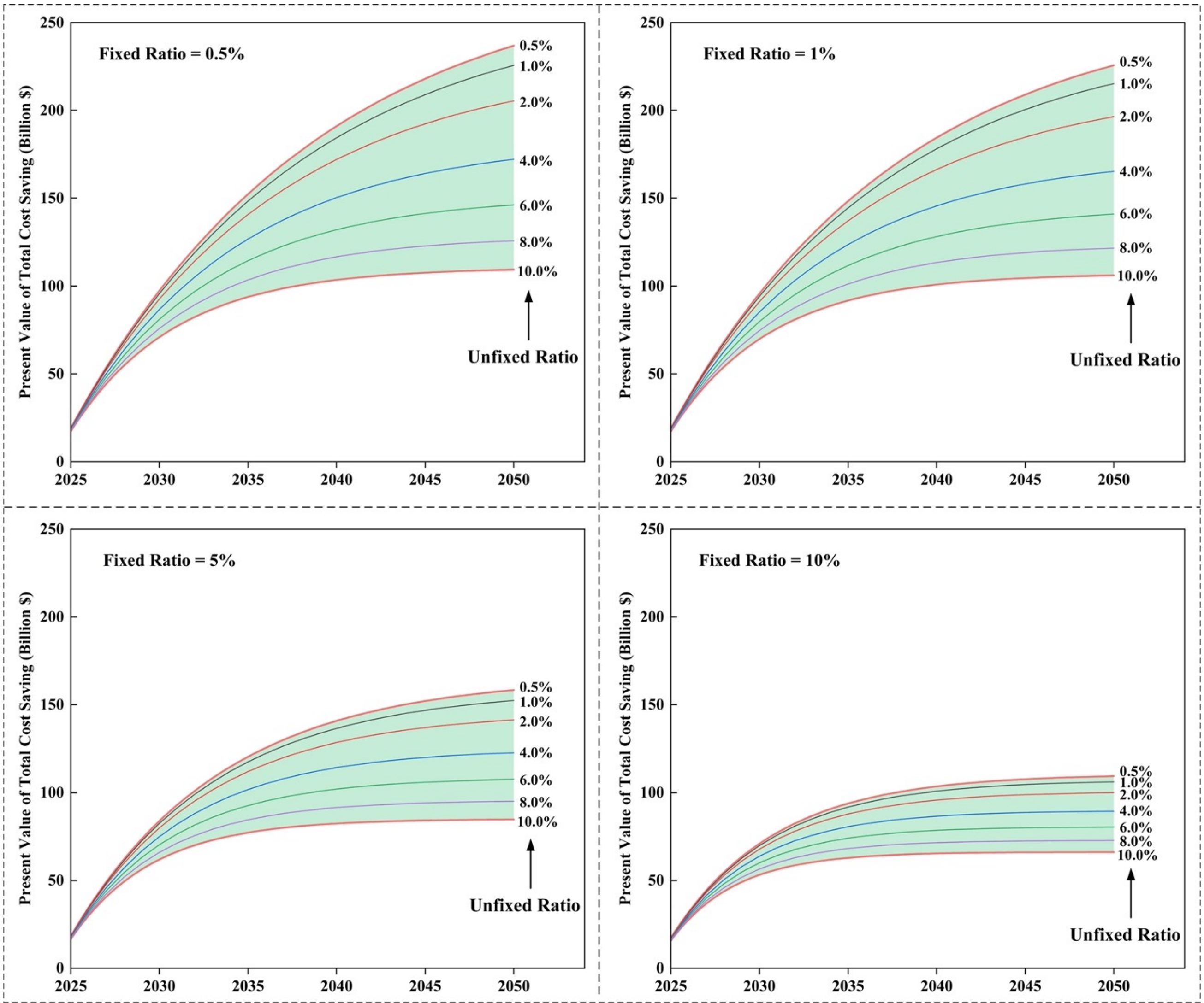

Fig. S4. Total cost saving under 1.5°C target.

Supplementary Notes

Note S1: Economic comparison with various cooling methods

The Levelized Cost of Energy (LCOE) is a widely used metric for comparing the energy costs of different technologies. It represents the average cost of constructing and operating an energy-generating system over its entire lifetime, divided by the total energy produced during that period. For cooling technologies, the associated costs include power generation, predevelopment, construction, operation and maintenance (O&M), as well as factors such as the discount rate, depreciation of fixed assets, and the potential residual value of those assets [8]. The equation for LCOE is expressed as:

$$\text{LCOE} = \text{total lifetime cost} / \text{total lifetime energy production}$$

$$= \left[\text{initial investment} - \sum_{n=1}^{N} \frac{\text{depreciation}}{(1+\text{discount rate})^n} + \sum_{n=1}^{N} \frac{\text{annual costs}}{(1+\text{discount rate})^n} - \frac{\text{residual value}}{(1+\text{discount rate})^n} \right] / \left[\sum_{n=1}^{N} \frac{\text{initial KWh} / \text{kW}_p \times (1-\text{ system degradation rate })^n}{(1+\text{discount rate})^n} \right] \quad (1)$$

where N is the lifetime and n is the n-th year. Depreciation and residual value are excluded in this analysis to simplify the evaluation process [8].

To enable a more intuitive comparison of the economic performance of various cooling technologies, this study introduces a Relative Operational Level (ROL) coefficient. The ROL is defined as the ratio of the LCOE of each cooling technology to that of a standard baseline system (pure photovoltaic, PV), providing a standardized metric for evaluating economic differences across systems. The parameters required for the LCOE calculation are detailed in Supplementary Table S1.

Annual O&M costs are inherently difficult to estimate with high accuracy and are treated as a variable in this study. For simplification, these costs are assumed to be a percentage of the initial investment. Similarly, the long-term data on energy generation improvements are limited, and thus, these are also treated as a variable. These assumptions enable a flexible and comprehensive evaluation of the economic performance of various cooling technologies across different scenarios.

For the economic performance analysis, 20-year bond yields from the United States, China, the United Kingdom, France, and Japan were chosen as the basis for determining the discount rate. These discount rates range from 1.95% (China) to 5.04% (United States), reflecting the long-term capital cost levels in major global economies [9]. Consequently, a discount rate range of 1% to 5% was adopted for the analysis. The relevant results are presented in Supplementary Figures S1 to S3.

It is important to note that the projected benefits of waste heat output are derived from a fundamentally conservative model. The analysis assumes that the available waste heat flux f is approximately equal to the electrical output. This assumption is grounded in the fundamental energy balance of a photovoltaic (PV) module under standard illumination. Typically, only about 20% of the incident solar energy is converted into electricity, while the vast majority (~80%) is absorbed and converted into heat, leading to the well-known phenomenon of PV operating temperature rise [Clean Energy Reviews. 2025; Available from: https://www.cleanenergyreviews.info]. Therefore, the waste heat flux is, in fact, significantly larger than the electrical output. The deliberate adoption of this equality is a conservative simplification that provides a robust lower-bound estimate of the potential economic and environmental benefits. The significant results projected under this conservative scenario strongly underscore the substantial potential of integrating thermal energy recovery with PV systems.

Note S2: Performance of IEWC technology in achieving the 1.5°C target

A quantitative assessment method is adopted to estimate the cost savings resulting from the reduction in installed capacity due to performance improvements in the IEWC (Integrated Evaporative Water-Cooling) technology. This method takes into account factors such as the rate of capacity reduction, improvements in system efficiency, and changes in capital expenditures, thereby providing a basis for evaluating the long-term economic impact of IEWC systems.

The annual cost savings from reduced installed capacity can be calculated as:

$$S_{\mathrm{n}}^{\mathrm{capacity}} = \left[f\left(x_{\mathrm{n}}\right) - f\left(x_{\mathrm{n}-1}\right) \right] \cdot r_0 \cdot \left(1 - g_e\right)^{\mathrm{n}-1} \cdot Cap_0 \cdot \left(1 - g_c\right)^{\mathrm{n}-1} \tag{2}$$

where $f(x_{\mathrm{n}})$ is the installed capacity of n-th year, r_0 represents the capacity reduction rate due to IEWC (i.e., the output power improvement ratio). Although experimental studies have reported r_0 exceeding 7% under seasonal conditions, a conservative estimate of 4% is adopted in this analysis to ensure robustness. g_e is the annual solar cell temperature coefficient reduction rate due to technological advancements, Cap_0 is the initial capital expenditure per GW, and g_c is the annual capital expenditure reduction rate due to technological advancements.

The present value of total cost saving over N years is the sum of annual savings (discount rate is adopted as 5%):

$$\text{Present Value of Total Cost Saving} = \sum_{\mathrm{n}=1}^{\mathrm{N}} \frac{S_{\mathrm{n}}^{\mathrm{capacity}}}{(1 + \text{discount rate})^{\mathrm{n}}} \tag{3}$$

To estimate the required photovoltaic installed capacity for future years, polynomial fitting model is developed using the known installed capacity for 2024 and the projected capacities for 2035 and 2050 [10]. The fitted polynomial equation is expressed as:

$$f\left(x_{\mathrm{n}}\right) = -8.830808042\left(x_{\mathrm{n}} - 2024\right)^2 + 1670.1024975524\left(x_{\mathrm{n}} - 2024\right) + 1852.3589 \tag{4}$$

The remaining resource savings primarily include reduction in land use (RLU), manufacturing-related greenhouse gas emission (RMG), and dissipated water use (RDW), which can be quantified using the following formulas:

$$\mathrm{RLU} = \sum_{\mathrm{n}=1}^{\mathrm{N}} \left[f\left(x_{\mathrm{n}}\right) - f\left(x_{\mathrm{n}-1}\right) \right] \cdot r_0 \cdot \left(1 - g_e\right)^{\mathrm{n}-1} \cdot Lu_0 \cdot \left(1 - g_l\right)^{\mathrm{n}-1} \tag{5}$$

$$\mathrm{RMG} = \sum_{\mathrm{n=1}}^{\mathrm{N}} \left[f\left(x_{\mathrm{n}}\right) - f\left(x_{\mathrm{n-1}}\right) \right] \cdot r_0 \cdot \left(1 - g_e\right)^{\mathrm{n-1}} \cdot Ge_0 \cdot \left(1 - g_{\mathrm{g}}\right)^{\mathrm{n-1}} \tag{6}$$

$$\mathrm{RDW} = \sum_{\mathrm{n=1}}^{\mathrm{N}} \left[f\left(x_{\mathrm{n}}\right) - f\left(x_{\mathrm{n-1}}\right) \right] \cdot r_0 \cdot \left(1 - g_e\right)^{\mathrm{n-1}} \cdot Dw_0 \cdot \left(1 - g_w\right)^{\mathrm{n-1}} \tag{7}$$

where Lu_0 is the initial land use per MW, g_l is the annual land use reduction rate due to technological advancements, Ge_0 is the initial manufacturing-related greenhouse gas emission per MW, g_g is the annual manufacturing-related greenhouse gas emission reduction rate due to technological advancements, Dw_0 is the initial dissipated water use per MW, and g_w is the annual dissipated water use reduction rate due to technological advancements. Since the statistical units of initial characteristics cannot be directly converted into values in units of GW (see Supplementary Table S2), the smallest practical photovoltaic power potential value at Level 1(Long-term yearly average of yearly totals), as presented in reference [11], is used as a conversion factor for scaling.

To account for additional water savings achieved through the integration of IEWC technology, the term WP_n is introduced to represent the annual volume of water produced in n-th year. It is assumed that the waste heat output is approximately equal to the electrical output, and the projected electricity generation is based on the forecast values from reference [12]. The water production is estimated by dividing the waste heat by the latent heat of water vaporization (corresponding to an initial water temperature of 18 ℃, consistent with observed system operation). This thermodynamic calculation provides a conservative, lower-bound estimate of the freshwater yield, as the actual available waste heat exceeds the electrical output and the specified latent heat value is relatively high. This enables the integration of waste heat-driven freshwater production into the evaluation of RDW.

$$\mathrm{RDW}^* = \sum_{\mathrm{n=1}}^{\mathrm{N}} \left[f\left(x_{\mathrm{n}}\right) - f\left(x_{\mathrm{n-1}}\right) \right] \cdot r_0 \cdot \left(1 - g_e\right)^{\mathrm{n-1}} \cdot Dw_0 \cdot \left(1 - g_w\right)^{\mathrm{n-1}} + \sum_{\mathrm{n=1}}^{\mathrm{N}} WP_{\mathrm{n}} \tag{8}$$

The final results of the long-term assessment under the 1.5°C target is summarized in Supplementary Fig S4 and Table S3. The underlying computational details, including parameter assumptions, annual projections, and model equations, are available in the accompanying file Impact of IEWC under 1.5°C target.xlsx.

Supplementary References

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