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Commentary

Passive interfacial cooling sparks a major leap in solar-driven water and power cogeneration

Shengyou Li[1], Kaiying Zhao[1], Eun Ae Shin[1], Gwanho Kim[1], Guangtao Zan[1,2,*]

[1] Department of Materials Science and Engineering, Yonsei University, Seoul 03722, Republic of Korea
[2] School of Chemical Science and Engineering, Tongji University, Shanghai 200092, China
*** Corresponding author:** Guangtao Zan, gtzan@yonsei.ac.kr

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Freshwater and electricity are foundational to human civilization's advancement. Yet, the duel against their scarcity intensifies as modernization progresses. Solar energy, hailed for its inexhaustibility and environmental friendliness, has emerged as a promising ally in generating both freshwater and electricity [1,2]. Despite significant interest and strides in solar cogeneration, the challenge of enhancing both freshwater and electricity outputs concurrently has stymied broader application. Recently, Mao and his research team introduced an innovative passive interfacial cooling (PIC) strategy within an inverted-structured solar-driven water-electricity cogenerator, which intensifies energy exchange between the power module and water module, markedly improving efficiency in cogenerating clean freshwater and green electricity [3]. This breakthrough, published in *Nature Water*, paves a new path for addressing the global scarcity of water and power resources [3].

Utilizing solar energy for the natural evaporation of water from surfaces is an age-old technique for producing clean freshwater, yet hampered by a low efficiency typically less than 0.5 kg m^{-2} h^{-1}. In recent years, with advancements in material science and nanotechnology, various interfacial solar vapor generators have been developed. Thanks to their exceptional photothermal effects, the efficiency of freshwater production has seen significant improvements. Recent studies have found that these solar vapor generators can do more than produce freshwater; they can also be coupled with other mechanisms for electricity generation. This electricity generation process fundamentally operates on two principles: 1) Hydrovoltaic power generation, wherein electricity is produced as water flows through the narrow channels of the active materials in a solar vapor generator, causing charge separation [4,5]. 2) Thermoelectric generation, which converts local temperature differences during the evaporation process into electrical energy through thermoelectric materials [6]. The former approach generally employs the same module for both water evaporation and electricity generation, and its performance is heavily dependent on the evaporator materials and type of liquid, which often results in unstable cogeneration performance and hinders practical applications. In contrast, the latter approach typically involves coupling a water evaporation module with a thermoelectric generator (TEG) module, enabling independent design and synergistic operation of the two modules. This configuration broadens the scope of applications and holds promise for substantially improved performance. Therefore, Lu's work just adopted the latter approach for cogeneration.

In previous solar-driven thermoelectric-water cogeneration works, research often focused on the material or structural design of individual modules, with little attention given to optimizing the energy exchange strategy between the power generation and water production modules. Additionally, most of previous thermoelectric-water cogeneration devices have adopted a structure where the solar vapor generator is connected to the upper surface of the thermoelectric generator. Such design is prone to salt scaling on the top of the vapor evaporator, significantly reducing solar absorption efficiency and hindering water evaporation. Moreover, in the above structures, as the temperature of bulk water rises, the temperature difference across the thermoelectric module gradually decreases until the module ceases to function. These issues have greatly hindered the high-performance realization of cogeneration devices, slowing their practical application [7].

In this study, Mao and colleagues introduced a PIC zone in an inverted-structured cogenerator system, aiming for superior cogeneration performance [3]. The system innovatively integrates a TEG above a solar vapor generator, leveraging four functional components: a top film layer combining polydimethylsiloxane and carbon black as the solar absorber for efficient photothermal conversion; a commercial TEG; an alumina heat sink placed at the bottom (cold side) of the TEG to enhance thermal conduction; and a trident-shaped evaporator made from directional freezing of polyurethane at the bottom (**Figure 1a**). The PIC zone, formed by inserting the alumina heat sink into the trident-shaped evaporator, provides a large area for heat sink-evaporator and evaporator-air interfaces. This innovative design significantly enhances energy exchange between the TEG, water evaporator, and the environment, effectively reducing heat loss and improving cogeneration performance (**Figure 1b**). Specifically, the high thermal conductivity of the heat sink facilitates rapid waste heat transfer from the power generation module to the water generation module. Then, the extensive heat sink-evaporator interface promotes effective heating of the evaporator, while the evaporator-air interface allows vapor to escape into the air, increasing the evaporation rate. Meanwhile, rapid water evaporation generates a significant amount of latent heat and quickly cools the cold side of the thermoelectric generator, which therefore increases the temperature difference across the power generation module and enhances electricity generation performance due to reduced convective and radiative losses. Besides, the latent heat of evaporation also helps absorb energy from the environment, further enhancing water production (**Figure 1c,d**). Thanks to this ingenious structural design, the PIC cogeneration system exhibited an ultra-high power density of 1.5 W m^{-2} and an exceptional water evaporation rate of 2.81 kg m^{-2} h^{-1} under one sun illumination, outperforming devices without the PIC effect by 328% and 158%, respectively (**Figure 1e**) [8–14].

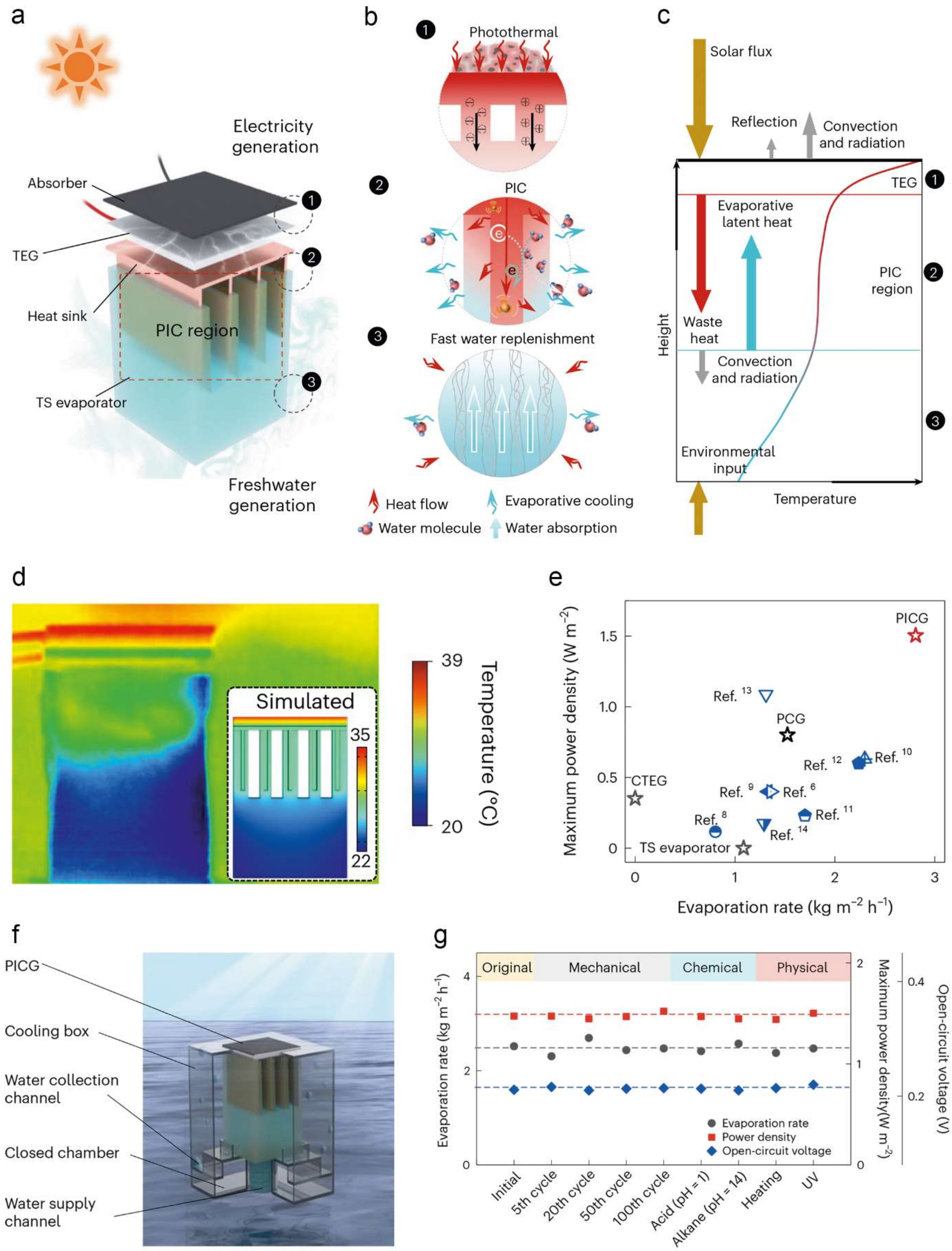

Figure 1. Design and properties of the passive interfacial cooling cogenerator (PICG). **(a)** The structure of the PICG. **(b)** Heat flows through the TEG, PIC region and bottom part of the evaporator (labeled as 1, 2 and 3, respectively) during the operation. **(c)** Enhanced energy exchange between the power generation and water evaporation modules enabled by the PIC region. Gold arrow: energy input; red arrow: waste heat; bule arrow: latent heat; gray arrow: convection and radiation heat loss. **(d)** Infrared images of the PICG under 1 Sun illumination. Insets: simulated temperature profiles. **(e)** Comparison of this work with some TEG-based power–water cogenerators. **(f)** Schematic of the 3D-printed inverted-structure PICG prototype. **(g)** Durability of the PICG under different conditions.

Furthermore, the cogenerator demonstrated excellent adaptability and universality. It operated stably under various harsh conditions and was adaptable to a range of liquids, including saline solutions, organic wastewater, and solutions containing heavy metals (**Figure 1f,g**). When integrated with a photovoltaic panel, the PIC strategy can significantly increase its power output from 55.7 W m^{-2} to 75 W m^{-2}, enabling charging real commercial electrical devices such as smartwatches and mobile phones, showcasing its outstanding versatility.

In conclusion, this work represents a major leap in the field of sustainable energy solutions. By introducing an innovative passive interfacial cooling strategy within an inverted-structured solar-driven water-electricity cogenerator, Mao and his team have successfully overcome traditional barriers in cogeneration technology [3]. This novel approach not only achieves unprecedented efficiency in simultaneously generating clean freshwater and green electricity but also demonstrates remarkable adaptability across diverse environmental conditions and fluid types. The cogenerator's ultra-high power density and exceptional water evaporation rate, significantly outperforming existing models, underscore its breakthrough potential. Furthermore, the system's compatibility with photovoltaic panels, enhancing power output for practical applications like charging electronic devices, illustrates its practical applicability and potential to revolutionize the renewable energy landscape.

Looking forward, it lays the groundwork for future innovations in sustainable energy systems, promising to address global challenges in water and electricity scarcity through scalable and efficient solutions. As we move towards an era increasingly reliant on renewable resources, the adaptability, and efficiency of such cogeneration systems will be paramount. This work not only paves the way for next-generation sustainable technologies but also inspires a new wave of research focused on eliminating the trade-offs between water production and electricity generation. It is a beacon of hope for achieving a more sustainable and resource-efficient future, where the harmonious coexistence of human progress and environmental stewardship is not just a vision, but a reality.

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