Harvesting energy from the sun and space: A versatile collector for simultaneous production of electricity, heat, and cold energy

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Dear Editor,

Electricity, heating and cooling are essential for modern buildings while incurring a vast energy consumption. In global, buildings consume around 40% of the total energy supply.[1] To address this challenge, efforts have been made worldwide to research and implement effective technologies for developing net-zero energy buildings. Green technologies based on renewable alternatives are thereby showing an increasing significance in such contexts. The sun (~5800 K) and the deep universe (~3 K) are extraterrestrially natural heat and cold sources that continuously transmit solar energy and cold energy to the Earth's surface. Efficient exploitation of both solar energy and the coldness of outer space is an appealing and ambitious solution to offer multiple types of renewable electricity, heating and cooling for buildings to meet their diverse energy demands diurnally and seasonally.

Photovoltaic (PV) and photothermal (PT) conversions are two dominant solar energy utilisation technologies that convert solar radiation into electricity and heat, respectively.[2,3] To fully utilise the solar spectrum of 0.2–3 μm, the well-known photovoltaic-thermal (PVT) technology featuring electricity and heat cogeneration has been proposed and developed.[4] Radiative cooling (RC) is an up-to-the-moment and utterly passive cooling technology via exploiting the transparent "atmospheric window" of 8–13 μm to dissipate waste heat to the cold space.[5] While PVT and RC technologies offer renewable energy solutions, they suffer from limitations in efficiency and flexibility. (1) Less efficiency. The power and thermal output of individual PVT collectors are constrained by the amount of solar irradiance received by the Earth's surface. To enhance PVT efficiency, solar concentrators like the widely used compound parabolic concentrator (CPC) have been proposed for integration with PVT panels.[6] The CPC enables the PVT system to receive 2~6 times more solar irradiance at near noon but it is ineffective during early morning and late afternoon when solar rays fall outside the acceptance angle of the CPC. For RC collectors, their cooling capacity is one order of magnitude lower than solar irradiance and is susceptible to environmental conditions (e.g., air humidity and sky-view factor).[7] In general, the RC collector demonstrates greater effectiveness when operated during dry nighttime periods in the absence of obstacle occlusion.[8] (2) Poor flexibility. The simultaneous deployment of both stand-alone PVT and RC collectors, with their ability to cogenerate electricity, heat and cold energy for buildings, faces obstacles due to limited roof or available space, as well as economic constraints. Conversely, opting for the individual deployment of either PVT or RC collectors in buildings results in a lack of applicability and flexibility to meet the diverse energy demands during different daily timeslots and seasons. Taking the PVT collector as an example, it is generally idle at night and is incapable of providing cold energy directly to help reduce the cooling load of the buildings, which impairs their practicability, particularly in hot seasons/regions.

Therefore, it is imperative to achieve the integration of solar energy and radiative cooling technologies, aiming to enhance the efficiency of both PVT and RC while ensuring versatility and flexibility for promising applications in buildings. This advancement will contribute to the promotion of net-zero energy buildings.

UNLOCKING HIGH EFFICIENCY, VERSATILITY, AND FLEXIBILITY: SIGNIFICANCE AND CHALLENGES IN PVT AND RC INTEGRATION

As two appealing renewable solutions, PVT and RC technologies have unique complementary characteristics in terms of energy outputs (electricity and heat vs. cold energy), preferable operating periods (cold seasons vs. hot seasons), and response spectrum selectivity (0.2–3 μm vs. 8–13 μm). These inherent complementarities create appealing significance for integrating PVT and RC technologies into a single collector, enabling 24-hour, versatile and flexible energy supply for buildings.

However, the integration of PVT and RC technologies also faces its fair share of challenges. One unignorable obstacle is the contradictory nature of the energy forms produced by PVT and RC collectors, namely heat and cold energy respectively. In this context, innovative structural designs are required for the integrated collector to effectively prevent any mutual interference or weakening effects between the two energy outputs. Furthermore, standalone PVT and RC collectors often struggle to generate energy in an efficient manner. Therefore, the development of an integrated PVT and RC system with the goal of promoting overall energy generation efficiency becomes even more challenging. This calls for the exploration of new structural concepts and advanced materials to overcome these hurdles and unlock the full potential of PVT and RC integration.

INNOVATIONS IN STRUCTURAL CONCEPTS AND MATERIALS TO BREAK THE IMPASSE

With the above ambitions, an innovative configuration with a newly designed transparent CPC (TCPC) module and advanced spectrally selective coating (hereafter referred to as "TCPC coating") is proposed to accomplish such an integrated and compact collector, named a transparent compound parabolic concentrator-based photovoltaic-thermal and radiative cooling collector (TCPC-PVTRC collector, Figure 1A). Its design philosophy and schematic are exhibited in Figure 1B. With the new structural concepts and advanced materials, this versatile collector overcomes the inherent drawbacks of inefficiency and inflexibility in standalone PVT and RC collectors, as well as the challenges associated with their integration.

New structural concepts and spectrally selective coatings

The proposed TCPC-PVTRC collector is mainly composed of arrays of miniature TCPC modules (only around 4 cm high) and PVT and RC modules. In a traditional CPC-PVT collector (Figure 1C), the CPC is generally structured by metal frames, and PVT modules are placed at the bottom of CPC slots. Transformed from the CPC, the TCPC module proposed in this project is a transparent solid, which perfectly incorporates PVT and RC modules at the bottoms of TCPC modules and TCPC slots, respectively, without expanding the installation footprint on the rooftop (Figure 1D). The TCPC module is initially configured as polymethyl methacrylate (PMMA), which has a gifted optical character of high solar transmission. In addition, by depositing a spectrally selective coating (i.e., TCPC coating), the wing surfaces of TCPC modules are endowed with distinctive spectral selectivity characteristics of high transmissivity in the solar spectrum of 0.2–3 μm and high specular reflectivity in the spectrum above 3 μm (including "atmospheric window" of 8–13 μm).

Principle

Such a TCPC module with a unique TCPC coating plays three critical roles in enabling the versatile functionality of the collector (Figure 1E). The first role is a thermal radiation blocker. The wing surfaces of TCPC modules can

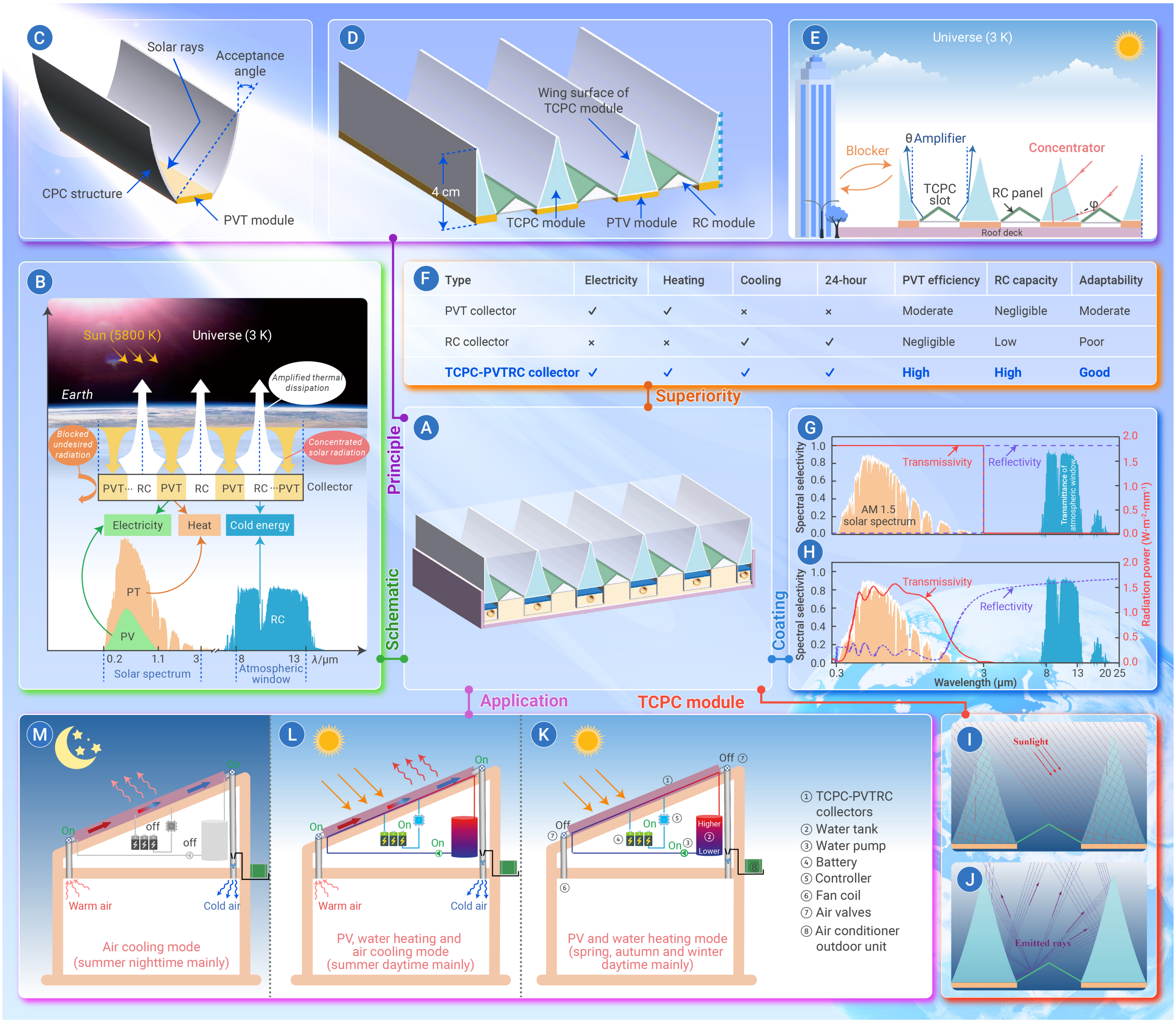

Figure 1. Versatile TCPC-PVTRC collector effectively integrating PVT and RC technologies (A) Configurational overview of the versatile collector. (B) Design philosophy and schematic detailing simultaneous harvesting of electricity, heat and cold energy. (C) Comparative illustration of a traditional CPC-PVT collector. (D) Key components highlighted in the versatile collector. (E) Innovative functionalities involved in design. (F) Summary of superiorities offered by the versatile TCPC-PVTRC collector. (G) Spectral characteristics of an ideal TCPC coating. (H) Spectral characteristics of a Tin-doped metal oxide film. (I) Traced incoming sunlight. (J) Traced emitted rays from the RC emitter panel. (K)~(M) Operation modes of the building integrated versatile collectors.

partially block thermal radiation from nearby surroundings (adjacent buildings, trees, etc.), ensuring that the RC emitter panel can exchange heat with the cold universe with minimal interference from nearby radiation sources (the building height in Figure 1E is indicative). The second role is a cooling power amplifier. The TCPC slot confines the hemispherical thermal radiation from the RC emitter panel transmitting through the atmosphere around the zenith direction (smaller θ) where the atmosphere is most transparent to significantly amplify the RC collector's cooling capacity throughout the day and night, thus enhancing its all-day availability. The last role is a solar concentrator. The TCPC module is capable of allowing the solar rays to pass through its wing surface and concentrate onto the PVT module by optical transmission mechanisms of refraction and reflection inside the PMMA.[9] Moreover, the inverted V-shaped design of the RC emitter panel effectively reflects sunlight onto the wing surface at a smaller incidence angle φ, ensuring TCPC modules' outstanding concentration performance during early morning and late afternoon hours. Such a solar concentrator, available throughout the daytime, considerably improves the PVT efficiency and operating stability. Based on the above innovations, the proposed TCPC-PVTRC collector can simultaneously generate electricity, heat and cold energy while efficiently utilising limited roof or space resources. In addition, it addresses the drawbacks of the stand-alone PVT, CPC-PVT and RC collectors in terms of working discontinuity, low PVT efficiency and cooling capacity, and poor regional/seasonal adaptability (Figure 1F).

Feasibility and preliminary validation

State-of-the-art materials like Tin-doped metal oxide film (Figure 1H) exhibit close-to-ideal spectral selectivity for TCPC coatings (Figure 1G),[10] yet there is still ample room for improvement. Leveraging the advancements in micro/nano technologies, such as particle doping, composite material synthesis and multi-layer coating, it is technologically possible to design and develop a TCPC coating with near-perfect spectral characters and excellent aging resistance. In terms of the availability of TCPC modules, PMMA stands out as a suitable material for solid TCPC modules owing to its high solar transmissivity and good durability. As exhibited in Figure 1I and J, the simulations based on the optical tool of TracePro demonstrate that the preliminarily designed TCPC module is capable of transmitting around 91% of the all-day solar rays falling into the TCPC slots onto PVT panels and reflecting above 95% of the RC emitter's thermal radiation outward the TCPC slot within a small zenith angle (less than 40°).

CONCLUSIONS AND PERSPECTIVES

The integration of PVT and RC technologies holds great potential due to their similarities in renewability and complementary nature in energy outputs, operating periods, and response spectrum selectivity. This ambitious solution aims to simultaneously provide electricity, heat and cooling energy, catering to the diverse energy demands of buildings across various scenarios. In this study, an innovative configuration named the TCPC-PVTRC collector, equipped with transparent compound parabolic concentrators and spectrally selective concentrator coatings, is proposed. Such a versatile and compact collector, fully exploiting renewable energy from both the sun and outer space, shows promise in overcoming the limitations of inefficiency and operational discontinuity in standalone PV, PT, RC, and PVT installations.

Additionally, the proposed versatile collector (with estimated dimensions of 2000*1000*100 mm) is well-suited for building applications as it can be easily installed by connecting collectors in parallel or series on the roof or façade and integrated with existing Heating, Ventilation, and Air Conditioning systems. The versatile collector enables exceptional energy supply flexibility and ensures regional and seasonal adaptability, making it an ideal choice for diverse building requirements. Specifically, it accommodates three main operation modes tailored to specific end-user demands (Figure 1K, L and M), namely, (a) PV and water heating mode mainly in spring, autumn and winter daytime, (b) PV, water heating and air cooling mode mainly in summer daytime, (c) Air cooling mode mainly in summer nighttime. This integrated technology exhibits immense potential due to its exceptional efficiency, flexibility, and economic advantages when compared to the aforementioned standalone devices.

Furthermore, the integration concept that combines PVT and RC technologies holds substantial application and market potential across various energy-hungry sectors, including industrial, agricultural and vehicle, etc., where there is a pressing demand for electricity, heat, and cold energy solutions. This innovative approach addresses the diverse needs of these sectors and presents a promising avenue for meeting energy requirements efficiently and sustainably.

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DECLARATION OF INTERESTS

The authors declare no competing interests.