PERSPECTIVE

Sustainable thermal energy harvest for generating electricity

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Electricity is the lifeblood of modern society. However, the predominant source of electricity generation still relies on non-renewable fossil fuels, whose combustion releases greenhouse gases contributing to global warming. The increasing demand for energy and escalating environmental concerns necessitate proactive measures to develop innovative green energy technologies capable of both cooling the Earth and generating electricity. Here, we look forward to an interdisciplinary power system integrating solar absorbers, radiative coolers, and thermoelectric generators. This system can simultaneously harvest thermal energy from the sun and from cold space, thereby transforming the challenges posed by global warming into opportunities for the production of clean electricity. We underscore recent advancements in this field and address key challenges while also exploring forward-looking opportunities in the foreseeable future. The proposed integrated energy technology achieves uninterrupted power supply through the unrestricted capture of thermal energy, offering a robust alternative pathway for next-generation sustainable energy technologies.

Electricity resources play a pivotal role in enhancing quality of life and sustaining industrial production. Global electricity consumption access to ~26,779 TWh in 2022, with a projected increase of ~9.3% by 2025. Non-renewable fossil fuels remain the dominant source of electricity generation, releasing greenhouse gases and thus leading to global warming. The Earth's temperature has risen by ~1.4°C since the Industrial Revolution, resulting in a surge of climate-related disasters by 2023. The escalating energy crisis and global climate change force us to explore cleaner sustainable energy sources, necessitating significant technological innovation and breakthroughs in basic research.[1]

The sun and cold space offer endless sustainable thermal energies for the Earth, rendering them ideal as green sustainable sources of electricity. The Earth's land surface can harvest an annual average heat energy of 250 W/m^2 from these sources. This substantial potential translates to an extraordinary total energy potential of 3.3×10^8 TWh per year, providing impetus for supplementing the existing green power system and catalyzing global energy transformation. The thermoelectric generator (TEG) is a solid-state heat engine, capable of directly converting heat into electricity with no moving parts, no emissions, no noise, a long lifetime, and maintenance-free operation. A solar absorber (SA) can absorb solar radiation to achieve solar heating, while a radiative cooler (RC) can selectively emit infrared radiation into the cold space to achieve radiative cooling. A TEG integrated with an SA and an RC can capture energy from the sun and cold space to achieve uninterrupted temperature difference (ΔT) and power generation throughout the day, promising a next-generation electricity technology (Figure 1A).

The sun (~6,000 K) provides essential energy for life on the Earth. SAs can capture incident sunlight and convert it into heat by photothermal effect. An ideal SA should exhibit high broadband light absorption across the full solar spectrum range (0.3–2.5 μm) with minimizing transmittance and reflectance.[2] Metal nanoparticles (e.g., Au, Ag, Pt, Te), with subwavelength size, leverage a unique localized surface plasmon effect. This effect confines the incident light into the nanoscale, intensifying the interaction between light and matter and thus generating heat through the Joule mechanism. However, these plasmonic metal nanoparticles predominantly absorb ultraviolet wavelengths, necessitating the meticulous arrangement or assembly of such particles to broaden their absorption bandwidth. Semiconductors (e.g., Ti_2O_3, Bi_2Te_3, $ZnFe_2O_4$) exhibit photothermal effects through electron-hole generation and relaxation under photoexcitation. Nevertheless, the radiation recombination of electron-hole pairs near the band-gap edge diminishes their solar heating performance. The introduction of in-band energy states, reduction of band gaps, and heteroatom doping can enhance the optical absorption characteristics of semiconductors. In addition, carbonaceous and polymeric materials with conjugated chemical structures (e.g., carbon nanotubes, graphene, carbon black) are widely employed as SAs due to their exceptional light absorption capabilities. The incorporation of additional components into conjugated polymers further broadens their light absorption range and suppresses photoluminescence emissions, thereby enhancing their photothermal performance. Beyond enhancing solar absorption, the reduction of mid-infrared thermal emission holds paramount importance in achieving spectral-selective absorption and improving photothermal performance.[3]

The cold space (~3 K) represents an abundant and timeless resource crucial for maintaining the Earth's energy equilibrium. Sky-facing RCs can emit thermal energy into cold space through the atmospheric transparent window (8–13 μm), thereby cooling terrestrial objects (~300 K) without any energy input. An ideal RC should exhibit precise wavelength selectivity to minimize sunlight absorption while maximizing the mid-infrared thermal emission. Polymers (e.g., polydimethylsiloxane, polymethyl pentene) possess numerous chemical bonds and functional groups enabling interaction with electromagnetic waves at vibration frequencies, facilitating broadband absorption of thermal wavelengths. Dielectrics (e.g., SiO_2, Al_2O_3, ZnSe) demonstrate robust absorption at mid-infrared wavelengths, attributed to phonon polaron resonance effects. Besides the material composition, micro-/nanostructures garner specific attention for finely tuning wavelength spectrum responses to achieve deep sub-ambient cooling. Scattering elements (e.g., particles, fibers, sheets, pores) in a uniform medium interact with incident photomagnetic waves, generating charge oscillations and forming a scattering field that regulates spectral characteristics.[4] Distributed Bragg reflectors and Fabry-Perot structures achieve near-perfect absorption and reflection of electromagnetic waves by leveraging multilayer structures with distinct optical characteristics.[5]

Advanced micro-/nanoengineering strategies (e.g., coating, hybrid, multilayer, porous, metamaterial, biomimetic structure) have been employed to regulate photothermal processes derived from solar heating and radiative cooling.[6] The state-of-the-art nanostructured SA exhibits nearly saturated light absorption and photothermal conversion efficiencies approaching 90%. Furthermore, the implementation of an external optical condenser allows the concentration of sunlight, elevating the SA's heating temperature from 100°C under ambient solar flux to 1,500°C, rendering it suitable as the hot end of a TEG to harvest energy from the sun. RCs have demonstrated the capability to achieve a theoretical cooling temperature drop of 60°C below ambient temperature in a vacuum, with an experimental reduction of 42°C realized under sunlight. The reported radiative cooling power has reached 156 W/m^2 at ambient temperature, establishing a promising cold sink for TEGs to harvest energy from the cold space.[5,7] Consequently, the sun and outer space emerge as sustainable thermodynamic resources for green electricity.

The TEG, comprising a heat source or a cold source, directly converts thermal energy into electricity through the directed movement of heat-driven carriers within materials. Figure of merit (zT) and efficiency (η) are key parameters for evaluating the performance of thermoelectric materials and devices, respectively. Micro-/nanoengineering strategies, such as doping/alloying, low dimension, nanocomposite, and nanoinclusions/nanopores, coupled with mechanisms like band modulating, energy filtering, and full-spectrum phonon scattering, are proposed to modulate the electron-phonon behavior to improve zT and η. Mainstream thermoelectric materials include BiTe alloys, organic composites, multicomponent oxides, Ag_2X (X = Te, Se, S), GeTe, $Mg_3(Sb, Bi)_2$, MgAgSb compounds, clathrates, I-V-VI_2 compounds, Mg_2Y (Y=Si, Sn, Ge), skutterudites, SnX, PbX, Cu_2X,

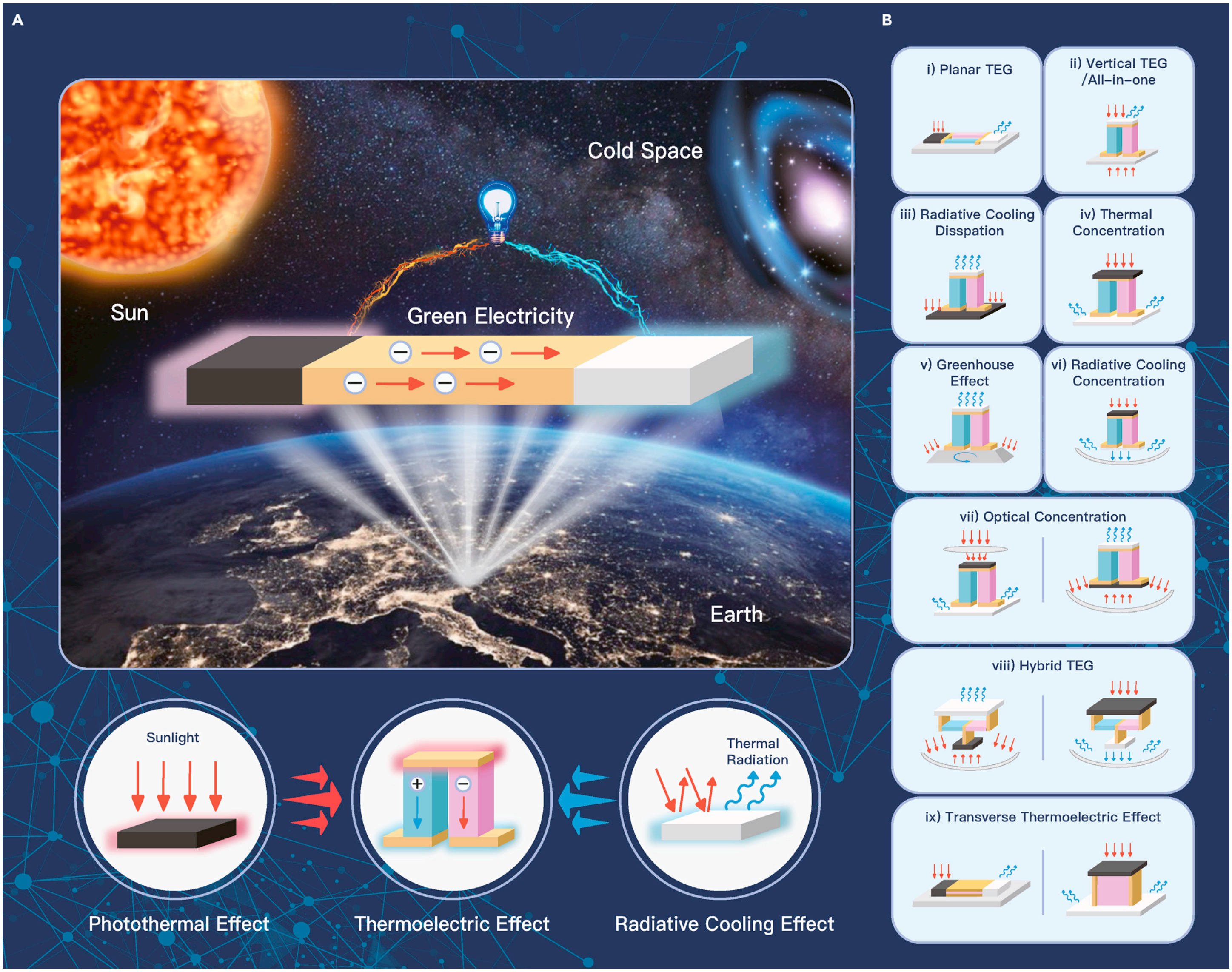

Figure 1. Harvesting thermal energy from the sun and cold space for green power generation (A) Schematic diagram of generating green electricity based on photothermal effect, thermoelectric effect, and radiative cooling effect. (B) Prototypes of the uninterrupted self-powering devices.

SiGe, half-Heuslers, etc.[7] Experimental zT values for room temperature BiTe-based materials are often around 1∼1.5, with a record value of 3.1 achieved at 783 K in SnSe. The η of the commercial TEG stands at ∼5%, while the experimental value has reached 15.2%.[7,8] These exciting outcomes elevate expectations for the application of TEGs.

The sun heats the TEG through the SA, while the cold space cools the TEG through the RC.[7] The η of the SA-TEG system, where solar-selective absorbers are integrated with segmented TE legs, reaches 7.4% with the addition of an optical condenser. Facing the night sky, the RC-TEG generated electricity during darkness, achieving an output exceeding 100 mW/m^2. Both the SA-TEG and the RC-TEG share similar structures and complement each other in function and working time.[9] In the emerging SA-TEG-RC device, the SA absorbs solar energy during the daytime, heating one end of the TEG, while the RC cools the other end throughout the day.[10] Consequently, an all-day ΔT is spontaneously established across the TEG, facilitating uninterrupted electricity generation. The theoretical η values of these integrated devices reach 13.7% and 40.5%, respectively, calculated using the experimental conditions for SAs (T_h = 100°C and 1,500°C), RCs (T_c = - 35°C), and TEGs (zT = 3). Harvesting 8% of the solar heating and radiative cooling power from one-thousandth of the Earth's land area could generate 2.6 × 10^4 TWh electricity, fully meeting the global electricity consumption demand in 2022.

Figure 1B illustrates typical emerging uninterrupted self-powering generators based on the SA-TEG-RC configuration. Planar TEGs are easy to prepare with long thermoelectric legs to build large ΔT (type i). However, they tend to exhibit elevated parasitic heat losses through the substrate. Vertical TEGs facilitate a relatively high level of integration with substantial heat utilization capacity, but their leg lengths are often shorter compared to planar types (types ii–vii). Hybrid TEGs can achieve both high integration and cross-plane heat flow but suffer from complex manufacturing processes and inevitable parasitic heat loss (type viii).

The SA and the RC at the two ends of a planar TEG can simultaneously face the sky without blocking each other, mitigating the interaction of emission/absorption in the vertical space (type i). Following Kirchhoff's law of thermal radiation, materials with broad-spectrum absorption also exhibit wide-spectrum emission. Consequently, the solar heating and radiative cooling capabilities of a material compete during the daytime. In type ii, only one material heats the end during the day and cools it at night, resulting in a reversed output current. Generally, the SA captures more energy per unit area from the sun than the RC dissipates during the day. In the integration of both the SA and RC with the TEG, optimizing their area ratio is critical to matching pumped-in and pumped-out energy, maximizing energy harvesting. The integration of a vertical/hybrid TEG with an SA and an RC is relatively complex (types iii–viii): (1) the thermal radiation of the SA may degrade the cooling performance of the RC, and (2) the coexistence of the SA, TEG, and RC in the same vertical space inevitably shrinks the effective area for solar heating or radiative cooling. Configuring a condenser in the TEG can solve the above problems, ignoring its extra cost burden (types vi–viii).

The ΔT and output performance of the integrated devices reported thus far are insufficient, particularly in their initial stage of development. In light of this, we reflect upon strategies to optimize these integrated devices: (1) employing optical concentration and thermal concentration, the SA can capture high sunlight flux, making it a desired heat source for the TEG (types iv and vii); (2) An RC with a proper larger area than the SA can dissipate more thermal energy into the cold space, thus balancing the pumped-in and pumped-out energy for TEGs (type iii); and (3) geometric optimization of TEGs is crucial for enhancing energy conversion efficiency. Utilizing segment thermoelectric modules with different operating temperatures contributes to the systems' output performance and extends their service life.

Harvesting energy from the sun and cold space for uninterrupted electricity generation represents an environmentally friendly technology that has long been desirable. Substantial advancements in the photothermal effect, radiative cooling effect, and thermoelectric effect have laid the groundwork for simultaneous energy capture and uninterrupted power generation. Nevertheless, the emerging SA-TEG-RC systems still face many scientific and engineering challenges, such as (1) ensuring strict spectral selectivity for the SA and RC, along with the high-performance TEG; (2) addressing the configuration and de-coupling challenges of the SA and RC within the integrated system; (3) implementing refined thermal management; (4) accounting for environmental factors and operating time; (5) incorporating additional storage for heat, cold, and electricity; (6) exploring further application of the transverse thermoelectric effect (type ix); and (7) striking a balance between the economy and energy savings.

The pivotal advantage of this compelling self-powering technology lies in its ability to deliver boundless, potent, and sustainable electricity output devoid of geographic and temporal constraints. This characteristic positions it as a decentralized alternative, particularly suitable for fulfilling the energy demand in isolated off-grid areas. We propose future opportunities and potential application scenarios for its upcoming growth as follows. (1) Small-scale personalized customization: this technology offers a continuous energy supply for micro-electronic devices such as micro-robots, sensors, unattended monitoring, etc. (2) Regional and global applications: it holds promise for large-scale pilot operations aimed at grid-connected power generation, utilizing global distribution of solar and cold space thermal energy. (3) Deep space exploration field: given the ultra-high vacuum environment, intense solar radiation, and low temperature in cold space, the integrated power system is poised to play an irreplaceable role in applications such as Earth-orbit satellites and extraterrestrial planet/deep-space exploration.

In this perspective, we have systematically sorted out the fundamental principles of the state-of-the-art energy harvester (SA and RC) and energy converter (TEG). We delve into recent advancements, optimal strategies, challenges, and opportunities for the simultaneous harvesting of thermal energy from the sun and cold space. This integrated, uninterrupted self-powering TEG, operating in tandem with solar heating and radiative cooling throughout the day, holds the promise of a bright future energy. It serves as a robust alternative pathway for next-generation energy technologies, paving the way for innovative applications across diverse domains. With ongoing optimized micro-/nanoengineered materials and integrated devices, this emerging technology is poised to exert a transformative impact on the global energy structure, contributing to environmental preservation and economic development.

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DECLARATION OF INTERESTS

The authors declare no competing interests.