Applications of radiative sky cooling in solar energy systems: progress, challenges, and prospects

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Abstract

The dynamic energy balance on the earth is jointly governed by solar energy harvesting and radiative sky cooling. Mainstream solar energy technologies, including photovoltaic conversion (PV), photothermal conversion (PT), and photovoltaic/thermal conversion (PV/T), as well as concentrated solar power (CSP) generation, have experienced significant progress after decades of developments. Recently, radiative cooling also saw significant advancements attributed to breakthroughs in material sciences and technologies. Though the energy transfer direction of solar energy collection and long-wave (above 3 μm) heat dissipation are poles apart, it is possible to combine the two mechanisms in one single system to exploit more energy from the universe. Radiative cooling has proved to be an effective way to either increase the PV efficiency by passively lowering the operating temperature of PV modules, or extend the working period of PT and PV/T collectors to nighttime and cold days via adding an extra passive cooling working mode, or enhance the thermal-to-power efficiency of CSP plants through declining the condensing temperature of the power block. This work conducts a comprehensive review and discussion on the history and recent advancements regarding the application of radiative cooling in different types of typical solar energy systems. Besides, existing challenges and possible opportunities involving combining the two ultimate renewable energy from outer space are concluded. This paper aims to provide a general summarization and possible guidance on the current status and future developments of radiative sky cooling applications in solar energy systems.

Keywords: *Radiative cooling; Solar collector; Solar photovoltaic; Photovoltaic/thermal; Solar thermal power.*

Abbreviations: Air mass, AM; Building-integrated solar photothermal conversion, BIPT; Building-integrated solar photothermal conversion and radiative cooling, BIPT-RC; Building-integrated solar photovoltaic conversion, BIPV; Building-integrated solar photovoltaic conversion, photothermal conversion, and radiative cooling, BIPV-PT-RC; Building-integrated solar photovoltaic conversion and radiative cooling, BIPV-RC;

Building-integrated radiative cooling, BIRC; Concentrated photovoltaic conversion, CPV; Concentrated solar power, CSP; Coefficient of performance, COP; Effective absorption, EA; Effective reflection, ER; Flexible photonic architectures, FPA; Heat transfer fluid, HTF; Heating, ventilation, and air-conditioning, HVAC; Low-density polyethylene, LDPE; National Renewable Energy Laboratory, NREL; Near-infrared, NIR; Phase change material, PCM; Photothermal conversion, PT; Photovoltaic conversion, PV; Photovoltaic/thermal conversion, PV/T; Polydimethylsiloxane, PDMS; Polyester, PET; Porous polymer coatings, PPCs; Polypyrrole, PPy; Radiative cooling RC; Scanning Electron Microscopy, SEM; Solar photothermal conversion and radiative cooling, PT-RC; Solar photovoltaic conversion and radiative cooling, PV-RC; Solar photovoltaic conversion, photothermal conversion, and radiative cooling, PV-PT-RC; Solar selective absorbing coatings, SSAC; Supercritical carbon dioxide, S-CO_2; Thermophotovoltaic, TPV; Vanadium dioxide, VO_2; Wet-bulb temperature, WBT.

Highlights

- Principles of radiative cooling and four solar energy technologies are introduced.
- Applications of radiative cooling in these solar energy systems are reviewed.
- Some current challenges and potential applications are presented and discussed.

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1. Introduction

The sun and the deep universe are respectively the ultimate heat and cold sources for the earth. Species on earth directly or indirectly acquire solar energy to sustain life activities. On a relatively short-time scale, despite a small portion of solar energy that rebounds to the sky or is converted into biomass energy (through photosynthesis), wind energy, ocean energy, etc., most solar energy projected onto the earth is absorbed and dissipated into heat rapidly. Without equivalent heat loss, the earth surface temperature will continuously increase, and all living organisms would wink out of existence due to the lack of suitable survival temperature. Thanks to the frigid outer space as a natural colossal heat sink, the earth endlessly sends a massive amount of heat there, and the temperature favorable for creatures is created on the earth. Although terrestrial objects can passively receive solar energy and radiatively dissipate waste heat to outer space, relevant technologies should be developed to enhance the utilization of solar energy or the universe's coldness depending on specific energy demands. The first strategy is a well-known and well-developed concept named solar energy utilization, while the second strategy is an anciently-existed but newly-developing technology called radiative sky cooling, or radiative cooling (RC) for short [1].

Among various solar energy utilization types, solar photovoltaic conversion (PV) and photothermal conversion (PT) and their combined form, solar photovoltaic/thermal conversion (PV/T) technology, are the most popular and developed ways [2]. Besides, solar thermal power is also a typical solar energy technology, in which solar energy is first converted into thermal energy by the PT process and then into electricity through a thermodynamic cycle [3].

Solar PV is a process that the PV cell traps photons from sunlight and releases electrons thereafter, which is well-known as the photovoltaic effect [4]. Photons with energy above the bandgap of solar cells induce the excitation of charge-carriers and thus current and voltage [5]. Though a solar cell with a positive temperature coefficient was developed recently [6], most solar cells perform progressively worse with the elevation in operating temperature. Since only above-bandgap photons can be partly converted into electric power, a PV module inevitably heats itself under sunlight exposure as most of the absorbed solar energy is dissipated into waste heat. Therefore, various attractive techniques aimed to lower the cell temperature were developed for the improvement of power conversion efficiency and reliability of the PV module [7]. Some predominant PV cooling technologies are water cooling [8], air cooling [9], refrigerant cooling [10], radiative cooling [11], etc. In general, water and refrigerant cooling techniques show better cooling performance but add complexity to the PV system, while air and radiative cooling techniques have simple structures but inferior cooling effect.

Solar PT is another dominant solar energy technology for heat collection. Upgrading solar energy absorption, downgrading heat losses (radiative and non-radiative), and enhancing heat transfer capacity are three main pathways to maximize the PT efficiency of a solar PT collector. The augment in solar energy absorption can be realized by increasing solar transmittance of the glass cover [12] and solar absorptivity of the absorber [13], and adding concentrating structures [14], etc. The reduction in non-radiative heat loss can resort to developing high-performing thermal insulation materials [15], creating a local vacuum environment [16], introducing convective barriers [17], and adopting multiple glass covers [18], etc. In order to lower the radiative heat loss, strategies such as the involvement of radiation shields [19] and low long-wave (above 3 μm) emissive coatings [20] have been applied. Generally, the receiver of a PT collector should have a very high absorptivity in the entire solar spectrum (i.e., 0.3 to 3 μm) but is expected to emit the minimum amount of heat in the middle- and far-infrared bands (above 3 μm).

Given the PV mechanism, the accumulated heat in a PV panel is inevitably generated but can be partly removed and utilized by cold fluid, which leads to the well-known solar PV/T technology [21]. Compared to a stand-alone PV or PT module, a PV/T collector takes the exploitation of solar energy throughout the solar spectrum and simultaneously produce electrical and thermal energy, resulting in a higher overall output efficiency [22, 23]. In the past decade, intensive research attention has been given to improve the thermal performance of the PV/T collector. Various types of PV/T collector have been developed, including water- [24], air- [25], heat pump- [26], heat pipe- [27], phase change material (PCM) based-collectors [28], etc. Similar to low-temperature solar PT collectors, the main application scenario of the PV/T collector is the building sector. Integrating PV/T collectors with the façade or roof can deliver clean electrical and thermal energy for buildings [29].

In addition to low-temperature solar PT applications, there is another category of solar thermal technology that firstly heats the heat transfer fluid (HTF) to a high-level temperature (usually above 400 °C [14]) through concentrated solar PT and then employs this high-temperature heat source to drive the power block, which is widely known as the concentrating solar power (CSP) technology [30]. A typical solar thermal power plant mainly includes the solar field, power block, and thermal storage unit [31]. The solar field, usually accounting for a large land area and consisting of many solar concentrator assemblies, captures the solar irradiation and reflects it to the receiver. The receiver heats up the circulated HTF inside to a high temperature [32, 33]. The HTF either flows back to the thermal storage unit before being sent to the heat exchanger or is directly pumped to the heat exchanger where its thermal energy is transferred to the working medium of the power block. The thermal storage system acts as an antifluctuator to store thermal energy during periods with intense solar irradiation and release it during cloudy/overcast hours and nighttime, making CSP plants superior to PV power plants in terms of operation continuity and stability [34].

Regarding radiative cooling, its real attraction lies in dumping waste heat into the cold universe without any driving energy, which offers a potential solution against global warming. The earliest scientific study on radiative cooling can be traced back to the 1960s [35], though this natural phenomenon has long been perceived and exploited. To radiatively cool down a terrestrial object itself, the emitted thermal radiation should be greater than the absorbed downward solar radiation and longwave thermal radiation from the sky [36]. Radiative cooling has experienced significant developments in the past decades, particularly in recent years, due to the breakthrough in daytime radiative cooling materials and devices [1]. Generally, the solar irradiance is one order greater than the thermal radiation flux of a radiative cooler, indicating that even a small fraction of solar energy absorption may render the cooler to above-ambient temperatures [37]. To achieve daytime radiative cooling, the emitter should present extremely high solar reflectance (usually above 0.9 [38], depending on the weather condition and emitter temperature) and strong emission in other spectra, especially within the "atmospheric window" (8 to 13 μm), in which the thermal radiation of the radiative cooler is mainly concentrated and the atmosphere shows high transmittance coincidently (see Fig. 1). Regardless of great efforts and achievements in accessing near-ideal radiative emitters, terrestrial radiative cooling performance is significantly affected by the local environment which is basically uncontrollable [39]. Being placed in a harsh environment (e.g., cloudy/overcast sky, strong solar irradiance, high-level relative humidity and wind velocity, and large air mass), a daytime radiative cooler will perform poorly or even be inactive provided sub-ambient cooling is targeted [37, 40]. However, radiative cooling will always be effective if only served as a heat dissipation solution such as removing parasitic heat from solar cells [11] or degrading the cooling load of buildings [41, 42].

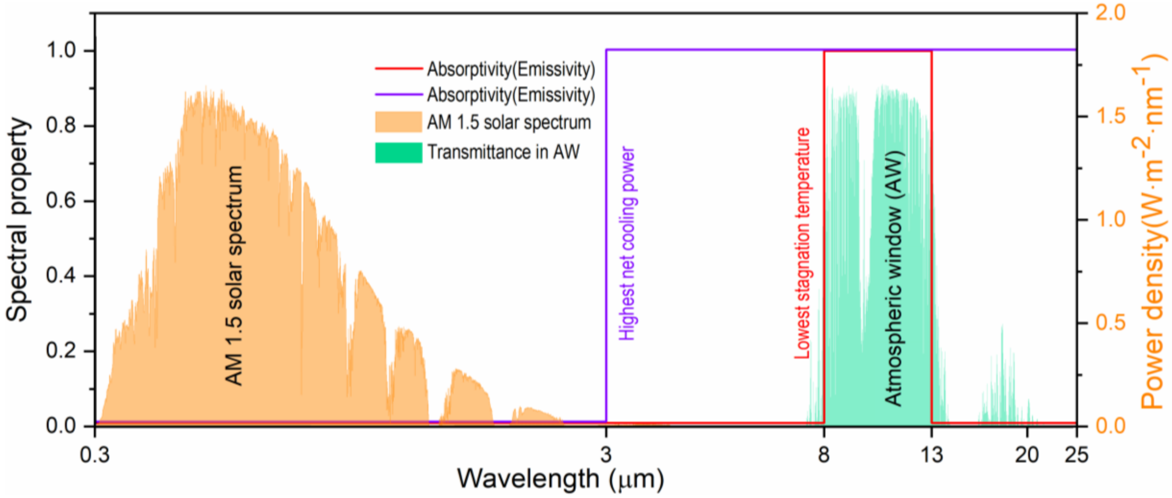

Fig. 1. Spectral properties of two ideal daytime radiative coolers. To achieve the highest radiative cooling flux, the radiative cooler should show zero absorptivity in the solar spectrum (0.3 to 3 μm) and 100% emissivity above 3 μm (purple line). To realize the lowest stagnation temperature, the radiative cooler should present 100% emissivity in the "atmospheric window" (8 to 13 μm) while zero absorptivity in the rest bands (red line). The AM 1.5 solar spectrum (orange zone) and typical atmospheric transmittance (green zone) are plotted for reference.

As solar energy and universe coldness are two ultimate energies to our earth and share the feature of renewability, cleanliness, and electromagnetism, it will be appealing and possible to comprehensively exploit them in a single system to maximize renewable energy utilization and system performance. It has long been recognized that the application of radiative cooling mechanism in solar energy installations can bring additional benefits in terms of multifunction, efficiency enhancement, continuous operation, seasonal flexibility, etc. For instance, radiative cooling can increase the PV efficiency by passively lowering the operating temperature of PV modules. The operation period of the solar PT and PV/T collectors can be extended to nighttime running as a radiative cooler. The thermal-to-power efficiency of a solar thermal power plant can be increased by dropping the condensing temperature with an additional radiative cooling strategy. In recent years, the application of radiative cooling in solar energy systems experienced remarkable advancements. Various techniques and structures have been developed to promote the integration of solar energy and radiative cooling. However, to the authors' best knowledge, no existing review paper conducted a thorough and systematic summarization and discussion regarding recent progress on this topic. Though numerous literatures reviewed on different solar energy technologies can be referred to, none of them focused on introducing radiative cooling in solar energy systems [43-46]. Likewise, though several recent review papers on radiative cooling briefly mentioned the combination of radiative cooling and solar energy technologies, the highlights of these works are the overview of fundamentals, materials, and applications [1, 47-50].

Therefore, this study carried out a comprehensive review regarding the application of radiative cooling in mainstream solar energy technologies. As the fundamentals of radiative cooling and different solar energy technologies have already been extensively summarized in existing literature reviews and are well-known by researchers in these fields, the present work emphasizes the application aspect of radiative cooling in different types of solar energy systems. Specifically, the passive cooling technologies for solar cells and PV modules via radiative cooling are summarized in Section 2. The current radiative cooling innovations on solar PT and PV/T collectors/systems are presented in Sections 3 and 4. The up-to-date applications of radiative cooling in solar thermal power systems are outlined in Section 5. And in Section 6, the challenges and prospects of integrating radiative cooling and solar energy technologies are discussed.

2. Radiative cooling in solar photovoltaic systems

Developing more reliable solar PV cells and modules with higher PV efficiency is vitally important for the broader application of this promising technology and is of great concern to academia and industry. Three losses, namely, optical loss, electrical loss, and thermal loss, inevitably accompany the photovoltaic conversion but can be suppressed to get a high-performing PV module. Lowering optical and electrical losses correspond to routes like improving the solar absorptance, minimizing the ohmic loss, and recombining photo-induced carriers, which is not the focus of this study. Thermal loss stands for PV efficiency decrement caused by parasitic heat in the PV module and thus provides radiative cooling an opportunity to mitigate it through passive thermal management. Thermal loss is inevitable as PV modules cannot fully convert absorbed solar energy into electricity. For instance, typical outdoor crystalline silicon PV panels can only convert a part of solar radiation in 0.3 to 1.1 μm range into electricity. Roughly 85% of solar energy is dissipated into heat, increasing cell temperature and aggravating the PV efficiency [2]. According to the fundamentals of energy balance for a solar cell, as illustrated in Fig. 2, increasing the conductive and convective heat losses ($P_{\mathrm{cond+conv}}$) can decrease the cell temperature and are the most well-known pathways for PV cooling, but it may also add structure complexity and operation cost.

Since a PV module is generally sunward mounted with a large sky-view factor, it can also adequately send waste heat to the cold sky through radiative cooling (see P_{rad} in Fig. 2). Therefore, it would be beneficial and attractive to lower the operating temperature and improve the PV efficiency via further enhancing passive radiative cooling. As the operating temperature of a PV module is generally higher than the ambient temperature when exposed to sunlight, the module should possess the highest possible long-wave emissivity to radiate the greatest possible heat to the sky. Bare solar cells generally show very low long-wave emissivity and thus presents poor radiative cooling capacity itself. Fortunately, an encapsulation layer is essentially set atop the cell layer of a commercial PV module and usually exhibits strong thermal emission (e.g., glass cover), thus radiatively cooling the PV module [51]. However, the spectral profile of the encapsulation layer can be further optimized to enhance PV efficiency. On the other hand, as a solar cell cannot convert sub-bandgap photons into electricity, it would be preferable to reject this part of solar energy to avoid generating additional waste heat.

For instance, low absorptivity within 1.1 to 3 μm will help decrease the operation temperature of crystalline silicon solar cells. In addition, though a practical solar cell always radiates thermal energy to cool itself, it unavoidably reflects a fraction of above-bandgap photons and absorbs a portion of sub-bandgap photons, which are adverse to the improvement of PV efficiency (see Fig. 3a).

According to the spectral optimization strategies involving radiative cooling, existing PV cooling works can broadly be categorized into three types of innovations, as the schematic illustrated in Fig. 3: (1) Enhancement of long-wave thermal radiation solely (see Fig. 3b), (2) Enhancement of above-bandgap absorption and long-wave thermal radiation simultaneously (see Fig. 3c), and (3) Enhancement of sub-bandgap reflection and long-wave thermal radiation simultaneously (see Fig. 3d). Besides, as conventional solar PV systems cannot operate at night, some other studies focused on combining diurnal solar PV and nocturnal radiative cooling in one single system.

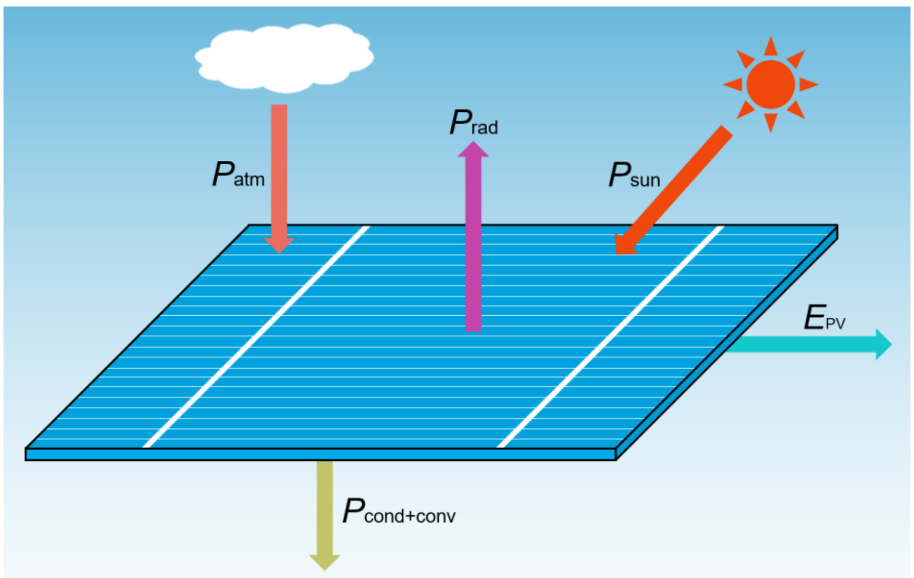

Fig. 2. Fundamentals of energy balance for a typical solar cell. P_{sun} is the absorbed solar energy, P_{atm} is the absorbed energy from the atmosphere, $P_{cond+conv}$ is the conductive and convective heat losses of the solar cell, E_{PV} is the output electricity of the solar cell, and P_{rad} is the outward radiative heat flux of the solar cell, in which radiative sky cooling is involved.

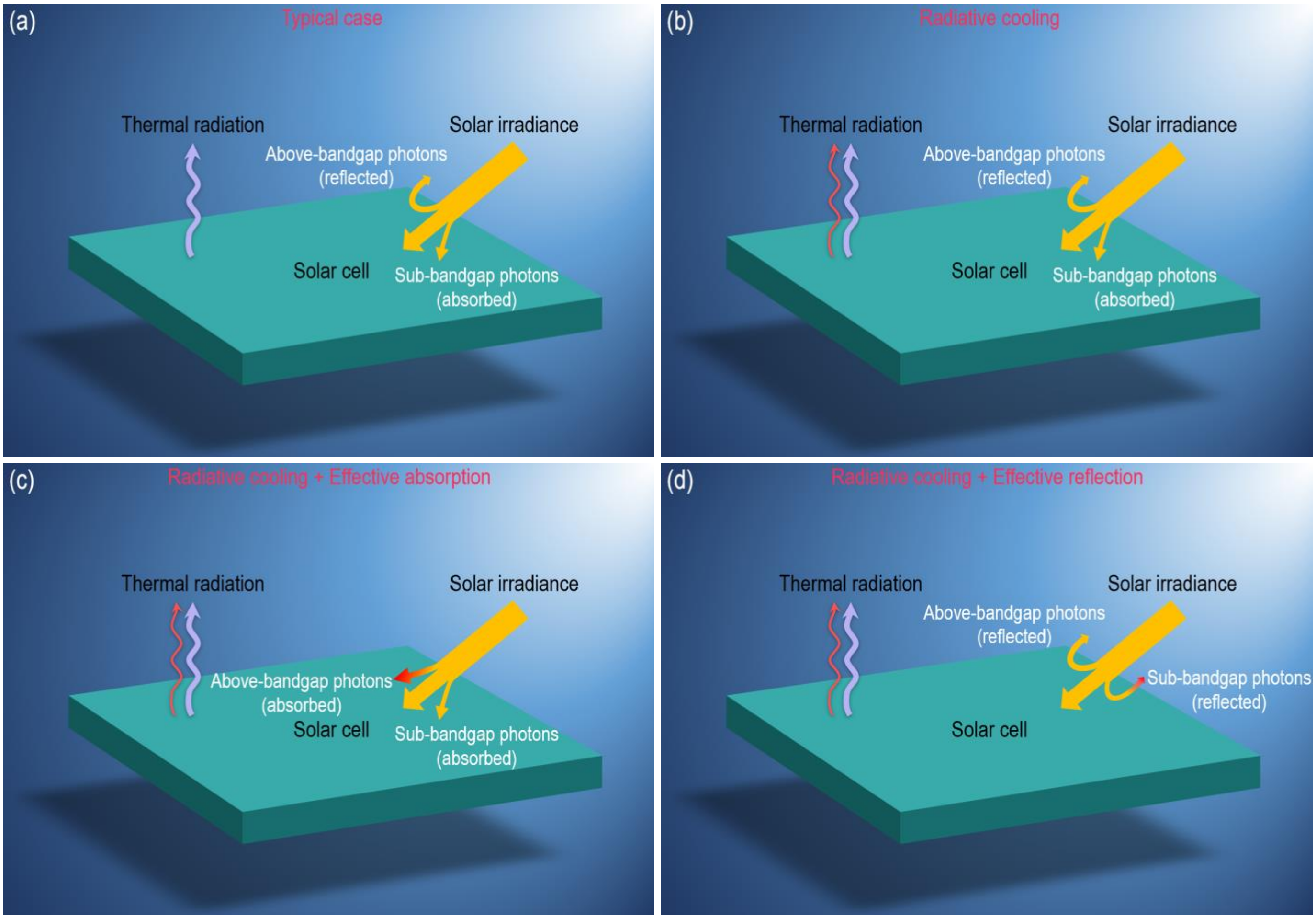

Fig. 3. Fundamentals of PV efficiency enhancement in a solar cell. (a) The typical case with no particular PV efficiency enhancement strategy, in which some above-bandgap photons (useful) are reflected and some sub-bandgap photons (useless) are absorbed. (b) PV efficiency enhancement using radiative cooling solely, in which thermal radiation flux is improved. (c) PV efficiency enhancement combining radiative cooling and above-bandgap photons absorption, in which thermal radiation flux is improved and more above-bandgap photons are absorbed. (d) PV efficiency enhancement combining radiative cooling and sub-bandgap photons reflection, in which thermal radiation flux is improved and more sub-bandgap photons are rejected.

2.1 Enhancement of long-wave thermal radiation solely

Enhancement of long-wave thermal radiation corresponds to improving the emissivity of the PV module outside the solar spectrum. Commercial PV modules such as the most popular crystalline silicon PV panel are usually equipped with a glass cover above the solar cells as a protection layer. Though current glass covers applied in commercial PV modules have already shown very high long-wave thermal radiation, there is still room for improving its radiative cooling capacity via increasing the long-wave emissivity, particularly in the "atmospheric window". As shown in Fig. 4, the glass cover generally exhibits a distinct emissivity dip around 9.6 μm caused by its strong phonon-polariton resonances. The emissivity dip near this wavelength will lead to a noticeable decrement in outward thermal radiation since the radiating power of objects with a surface temperature of around 320 K (a typical operating temperature of the PV module [52]) peaks at about 9 μm.

Therefore, the emphasis of enhancing the long-wave thermal radiation of a PV module lies in filling up this emissivity dip or replacing the glass cover with another structure that shows mitigated emissivity dip. Results suggested that erasing the emissivity dip within the atmospheric window can enhance the radiative cooling flux by around 10% [53]. Generally, compared to the origin of solar PV technologies and applications, the research of decreasing the cell temperature by radiative cooling started rather late and is still in its early stage.

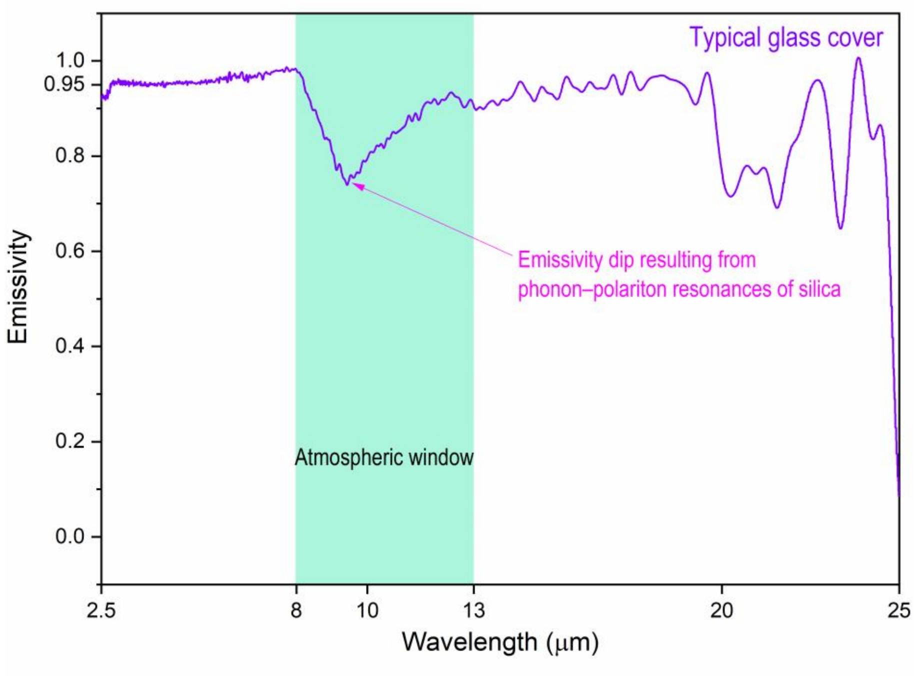

Fig. 4. Spectral emissivity (2.5 to 25 μm) of the typical glass cover atop the commercial solar cell. The emissivity dip within the atmospheric window is caused by strong phonon–polariton resonances of silica.

The quantum radiative cooling technique for textured solar cells was developed by Gilman and Ivanov [54] to achieve additional long-wave emission from the PV module. This quantum-assisted thermal emission allows the PV module to cool itself by 5 to 20 °C and earn 3% to 10% efficiency improvement. The benefit of improving the PV efficiency through radiative cooling has not attracted extensive attention until Zhu et al. [55] proposed the ideal spectral profile of the radiative cooler on top of the solar cell and demonstrated a micro-photonic structure based on silica (SiO_2). As shown in Fig. 5, the authors designed a 2D square lattice of SiO_2 pyramids and a 100-μm-thick uniform SiO_2 layer atop a bare silicon layer (the bare silicon layer is regarded as the bare solar cell in this study) and realized almost unity emissivity above 4 μm, resulting in a 17.6 °C temperature reduction and a 7.9% relative efficiency increment compared with the bare solar cell at 800 W/m^2 solar heating flux. Wu et al. [56] demonstrated that the performance of a GaAs nanowire solar cell could be improved by radiative cooling as well. By coating the nanowires with a transparent polymer which is transparent to solar radiation but emits strongly in mid-infrared spectra, the GaAs nanowire solar cell gets a temperature decrement of almost 7 °C and an absolute efficiency increment of about 0.5% attributed to radiative cooling, compared to that of the planar GaAs structure.

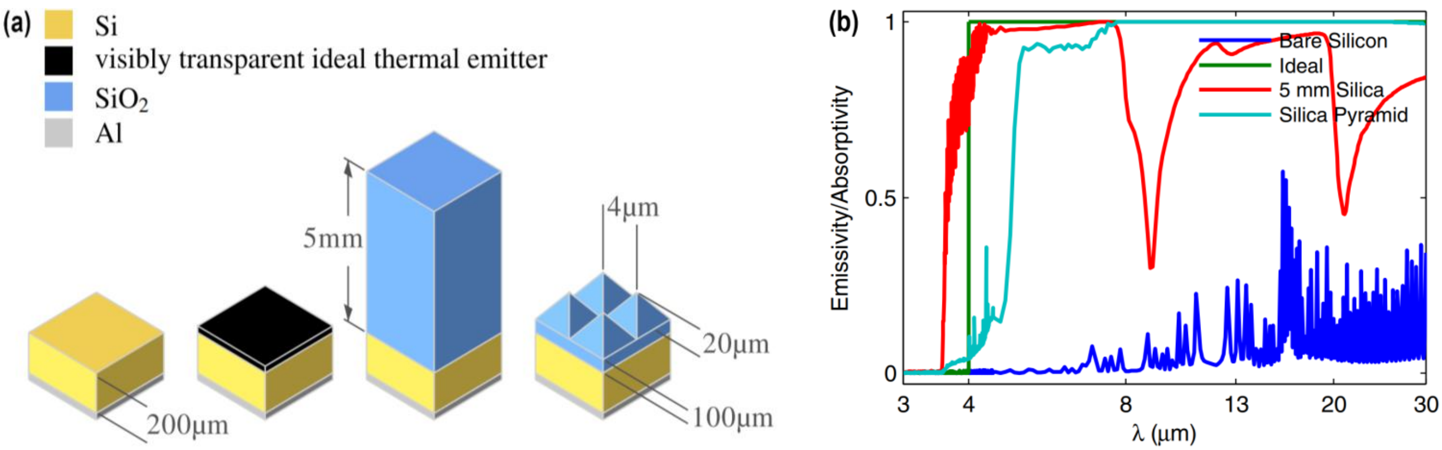

Fig. 5. (a) Schematic of four structures based on silicon (bare silicon, Ideal thermal emitter, 5-mm-thick silica, and silica pyramid, from left to right) [55]. (b) Corresponding spectral properties of the four structures at 300 K [55]. (a) and (b) are reprinted with permission from Zhu et al., *Optica* 1(1), 32–38 (2014). Copyright 2014 Optical Society of America.

Owing to its blackbody-like spectral property in mid-infrared wavelength, the polydimethylsiloxane (PDMS) has proved to be a high-efficiency thermal radiator for cooling outdoor objects [57-59], including PV devices [60-63]. Zhao et al. [61] added a PDMS film atop a commercial glass-covered solar cell to enhance the long-wave emissivity, and a 1 °C temperature reduction was experimentally demonstrated compared to the commercial structure, corresponding to a relative efficiency increment of 0.45%. Lee and Luo [62] designed a pyramid-structured PDMS layer and arranged it as the transparent cover of three types of flexible thin-film solar cells. Simulation suggested that, compared to the planar PET-covered solar cell, the PDMS structure helps cool an organic, a perovskite, and a micro-crystalline silicon flexible solar cell by 11 °C, 12 °C, and 16 °C, respectively. Wang et al. [63] designed and prepared a pyramid-textured PDMS film to radiatively cool encapsulated commercial silicon solar cells. Experimental results revealed that a 2 °C temperature reduction was contributed by the PDMS film, corresponding to a relative efficiency improvement of about 1%.

Compared to the radiative cooling process on the earth surface, radiative cooling will play a more critical role in cooling PV devices located in the extraterrestrial environment where the radiative cooling flux is greater and no other cooling approach can be resorted to [61, 64, 65]. Provided the device proposed by Zhao et al. [61] was located in an extraterrestrial environment, the PDMS film could lower the operating temperature of the solar cell by 4.1 °C and increase the PV efficiency by 1.85% relatively. Safi and Munday [64] proposed an ideal structure to radiatively cool the solar cell in both terrestrial and extraterrestrial environments. The designed structure yields an efficiency improvement of 0.87% compared to a typical PV module in a terrestrial operation condition and an efficiency augment of up to 2.6% when applied in near-earth orbit. Banik et al. [65] designed and prepared a layer of silicon-oxycarbonitride coating on the CIGS solar cell and successfully enhanced the thermal emissivity of the cell from 0.3 to 0.7. Simulation results suggested that this coating can lower the cell temperature up to 30 °C in orbit, corresponding to about 27% increment in maximum power output.

As radiative cooling energy density increases dramatically with the surface temperature, this cooling strategy will be more effective for those PV modules working in high temperatures, such as thermophotovoltaic (TPV) modules [66, 67] and concentrated photovoltaic (CPV) modules [68, 69]. Since one side of the PV diode faced the thermal radiator (around 1500 K) is generally exposed to a vacuum environment in the TPV module, the convective cooling mechanism is only effective on the other side where a heat spreader with a larger area is usually attached to. Therefore, the operation temperature of the PV diode can be further cooled down via radiative cooling if the heat spreader is also a strong thermal emitter. Adding a radiative cooler such as a low-iron soda-lime glass photonic crystal to the heat spreader of the PV diode, the operation temperature of the PV diode can be reduced by 91 °C, leading to a PV efficiency enhancement of 18% relatively, provided the area of the radiative cooler is 10 times larger than that of the PV diode [66]. However, the benefit derived from radiative cooling may be marginal at a large convective heat transfer coefficient if the radiative cooler is not much larger than the PV diode in size [67]. Sun et al. [68] explored the effectiveness of radiative cooling mechanism in declining the operation temperature of a concentrated PV module equipped with a parabolic reflector as the concentrator (see Fig. 6a). A multi-layer low-iron soda lime glass with high solar transmittance and strong thermal emissivity is placed on the sky-facing side of the PV module. High solar transmittance of the glass allows the sunlight to pass through it before being concentrated in the PV module. Therefore, the PV module can be cooled partly by the large-area glass emitter through radiative cooling. Compared with a conventional copper cooler, the glass cooler can degrade the operation temperature of the PV module by 14 °C more. Zhou et al. [69] developed a radiative cooling-assisted CPV module with an infrared-transparent Fresnel lens concentrator. As shown in Fig. 6b, a radiative cooler made up of a soda-lime glass layer, and an aluminum reflector was set on the heat spreader of the solar cell. Compared to the benchmarked CPV module without the radiative cooler, a 10 °C temperature reduction of the radiative cooling-assisted CPV module was experimentally observed, corresponding to a 5.7% relative increment in open-circuit voltage and 40% extension in lifetime at 13 suns. In a following study, Wang et al. [70] deployed a Fresnel lens-based CPV system integrated with two-sided radiative coolers (see Fig. 6c). By attaching two soda-lime radiative coolers on both surfaces of the heat sink, a 5 to 36 °C temperature reduction and an 8% to 27% relative increase of open-circuit voltage for a GaSb solar cell were experimentally demonstrated. A summary of some references regarding PV cooling technologies with radiative cooling enhancement solely is shown in Table A1.

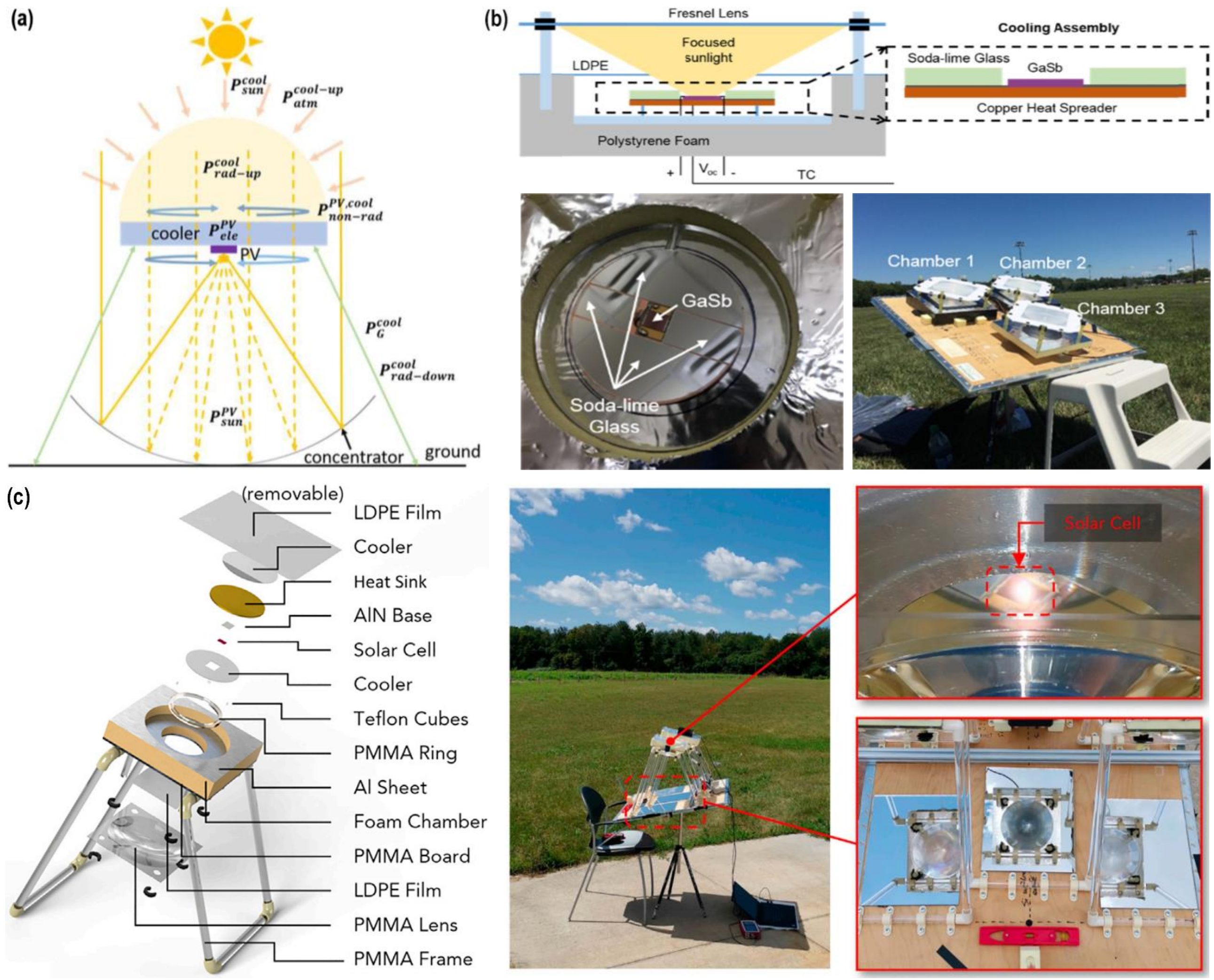

Fig. 6. Radiative cooling structures for concentrated PV modules. (a) A concentrated PV with a large-area low-iron soda lime glass cooler atop the sky-facing side of the PV module and a parabolic reflector as the sunlight concentrator [68]. Reproduced with permission from Sun et al., *Proc. of SPIE* 10369, 103690D (2017). Copyright 2017 SPIE. (b) Schematic and in-situ experimental setup of a radiative cooling-assisted concentrated PV system with an infrared-transparent Fresnel lens concentrator and copper heat spreader [69]. Reprinted with permission from Zhou et al., *Opt. Express* 27(8), A404–A418 (2019). Copyright 2019 Optical Society of America. (c) Schematic and outdoor experimental setup of a Fresnel lens-based concentrated PV system integrated with two-sided radiative coolers [70]. Reproduced with permission from Wang et al., *Joule*. 4, 1–16 (2020). Copyright 2020 Elsevier.

It is admitted that the effect of enhancing radiative cooling solely on further improving the efficiency of a benchmarked PV module already covered by a high-emissive glass is indistinct [7, 61, 67, 71]. However, the radiative cooling mechanism can work together with the spectrally selective optimization of the PV module in the solar spectrum to boost the output performance of the module. In general, increasing the above-bandgap solar absorption of the solar cell can reduce the optical loss, while lowering the sub-bandgap solar absorption of the solar cell can degrade the thermal loss. Details regarding the combined effect of radiative cooling and selective solar absorption on the PV efficiency are presented in the following two sections.

2.2 Enhancements of above-bandgap absorption and long-wave thermal radiation simultaneously

Any spectral modification that can enhance the long-wave thermal radiation of the solar PV module should be appreciated but may bring unexpected side effect of increasing the optical loss [72]. The benefit resulted from enhancing the long-wave thermal emission of the atop cover is easily wiped out by degrading its above-bandgap solar transmittance. Therefore, the new structure added on top of the solar cell should present the same or even higher transmittance in the above-bandgap regime (e.g., 0.3 to 1.1 μm for crystalline silicon solar cells, and 0.3 to 0.87 μm for GaAs solar cells) compared to the original encapsulation layer [61]. To objectively demonstrate whether or not a new design is favorable for improving the performance of a PV module, the PV efficiency [60, 73] should be adopted as the final performance indicator rather than the operating temperature of solar cells only [74-76].

Compared to the strategy that only enhances radiative cooling, combining approaches of strengthening above-bandgap solar absorption and radiative cooling can improve the PV efficiency some more. Based on a double-side-polished silica wafer, Zhu et al. [74] developed a photonic crystal-based solar absorber by adding a visibly transparent photonic crystal radiative cooler atop a crystalline silicon wafer via a thermophotonic approach (see Fig. 7a). The added photonic crystal radiative cooler makes the solar absorber as a whole show near-perfect long-wave emissivity and higher solar absorption (see Fig. 7b). Experimental results revealed that the photonic crystal-based solar absorber could be radiatively cooled by 13 °C if the solar absorber is well-isolated from ambient air. The authors also repeated the experiment after removing the polyethylene cover to allow the solar absorber to operate in a real scenario. Under the effect of radiative and non-radiative cooling mechanisms combination on the temperature reduction, the stagnation temperature gap between the photonic crystal-based and bare solar absorbers narrowed sharply but still reached 5.2 °C. However, compared to the planar silica-based solar absorber (emulate the commercial PV module), the temperature reduction of the photonic crystal-based one is only 1.3 °C. On the other hand, although the silicon wafer is p-doped with a resistivity of 1 to 10 Ω·cm to emulate the feature of an actual bare silicon solar cell, its spectral property is still distinct from the commercial bare silicon solar cell, especially in the sub-bandgap spectrum (i.e., 1.1 to 3 μm) [61]. Unlike the silicon wafer in Ref. [74], the commercial bare silicon solar cell shows high absorptivity in the sub-bandgap regime, which will create additional local heat load and deteriorate the performance of the solar cell. However, this reality also provides a chance for the PV efficiency improvement by cutting down the spectral absorptivity in the sub-bandgap range, which is detailly discussed in Section 2.3.

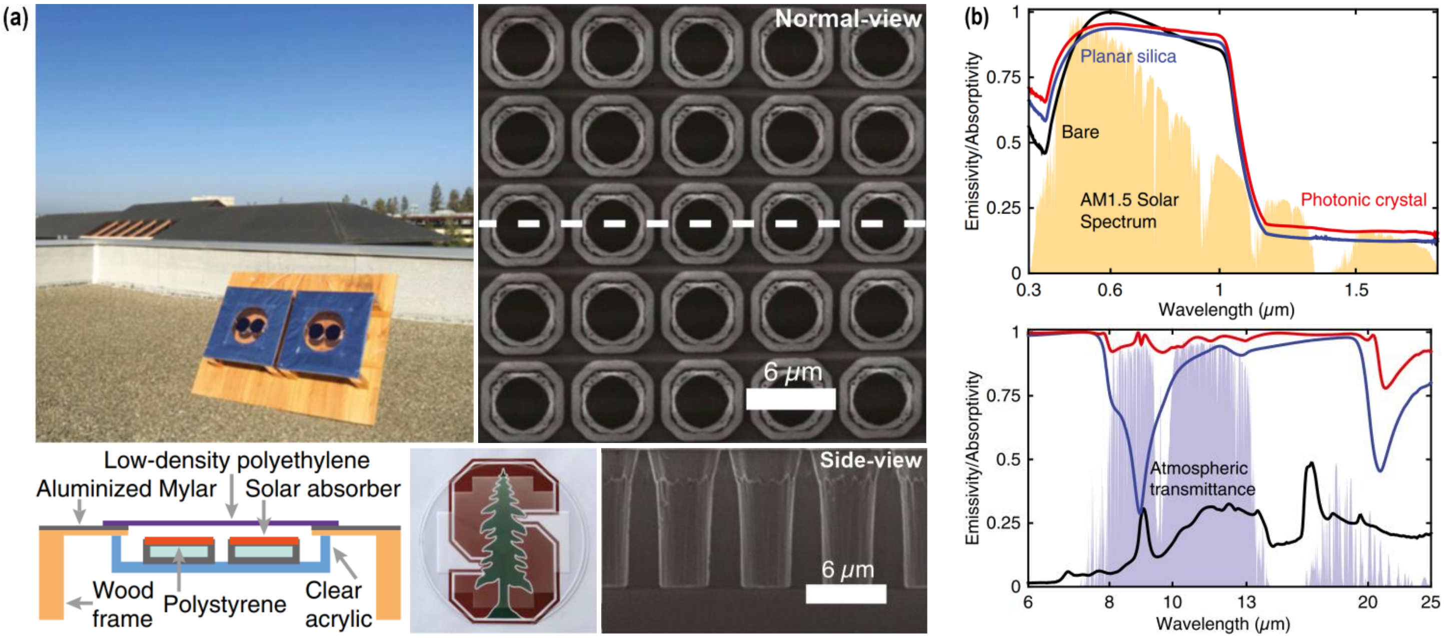

Fig. 7. (a) Cut-out schematics and rooftop experimental apparatus of a 2D silica photonic crystal-based solar absorber and in-situ experimental rig, normal- and side-view SEM images of the photonic crystal structure [74]. (b) Measured emissivity/absorptivity of the photonic crystal-based solar absorber from the ultraviolet to middle-infrared bands [74]. (a) and (b) are reproduced with permission from Zhu et al., *PNAS* 112(40), 12282–12287 (2015). Copyright 2015 National Academy of Sciences.

Lu et al. [60] proposed a cost-effective, durable, and energy-efficient approach to achieve both radiative cooling and light management through sol-gel imprinted ultrabroadband textures. The textures show near-perfect emissivity higher than 0.96 within the "atmospheric window" and transmittance over 0.94 within the visible spectrum, which is identified as an excellent encapsulation cover for solar cells. The PV module covered by the textures imprinted glass realizes a relative increment of 3.13% in the PV efficiency, benefited from greater thermal emission and above-bandgap solar absorption. In a following research, Lin et al. [77] prepared flexible photonic architectures (FPA) on polydimethylsiloxane (PDMS) and then electrostatically attached the FPA-PDMS structure to the encapsulant cover of the solar cell, as shown in Fig. 8. The FPA-PDMS structure alone showed an average transmittance of near 97% and haze of about 96% within the above-bandgap regime, together with an average normal incidence emittance of 0.98 within the "atmospheric window", earning a PV efficiency improvement of 6.75% and 3.23% respectively for the perovskite and crystalline silicon solar cells under the standard test condition. Aiming to simultaneously improve solar absorption and radiative cooling, Long et al. [75] designed and fabricated a thin SiO_2 micro-grating coating as the encapsulation cover of a doped silicon wafer. Outdoor experiments indicated that the SiO_2 micro-grating achieved an additional decrement in cell temperature by 2 °C compared to the bare doped silicon wafer. Kumar and Chowdhury [78] selected and compared the behavior of several different inorganic substances that served as both the antireflection coating for improvement of solar absorption and the radiative cooling layer for enhancement of mid-infrared thermal emission. The simulation-based research revealed that Si_3N_4 is a good candidate in helping the crystalline silicon solar cell to improve the above-bandgap absorption and long-wave thermal radiation and lower the operating temperature. Compared to the SiO_2 layer-covered solar cell, the Si_3N_4-based one absorbs 25 W/m^2 more solar radiation in 0.3 to 1.2 μm range and radiates 16.2 W/m^2 more heat in the "atmospheric window", increasing the PV efficiency by about 1% in absolute scale. In their following study, Kumar and Chowdhury [79] proposed the design of adding a selective radiative anti-reflective coating atop the commercial single-layered Si_3N_4 coated multi-crystalline silicon solar cell (Si_3N_4/mc-Si_{wafer}). This strategy is expected to lower the cell temperature via enhancing radiative cooling and meanwhile to keep or improve the solar absorption in 0.3 to 1.15 μm range. Simulation results indicated that, compared to the Si_3N_4/mc-Si_{wafer} module, the $SiO_2/Al_2O_3/Si_3N_4$/mc-Si_{wafer} structure can achieve an additional 14 W/m^2 solar energy absorption and 124.4 W/m^2 long-wave thermal emission, corresponding to a temperature reduction of 5.45 °C and a PV efficiency improvement of 3.6% when the solar radiation, ambient temperature, wind velocity are respectively 1000 W/m^2, 30 °C, and 1m/s. Perrakis et al. [80] designed a nano-micro-structured glass grating coating on top of a simple-planar Si substrates, resulting in a relative solar absorption enhancement of about 25.4% and a cell temperature reduction up to 5.8 °C. A relative PV efficiency increment of around 3.1% is further achieved after applying the nano-micro-structured grating to a commercial PV cell. Table A2 presents a summary of some PV cooling technologies involving radiative cooling and above-bandgap absorption enhancements simultaneously.

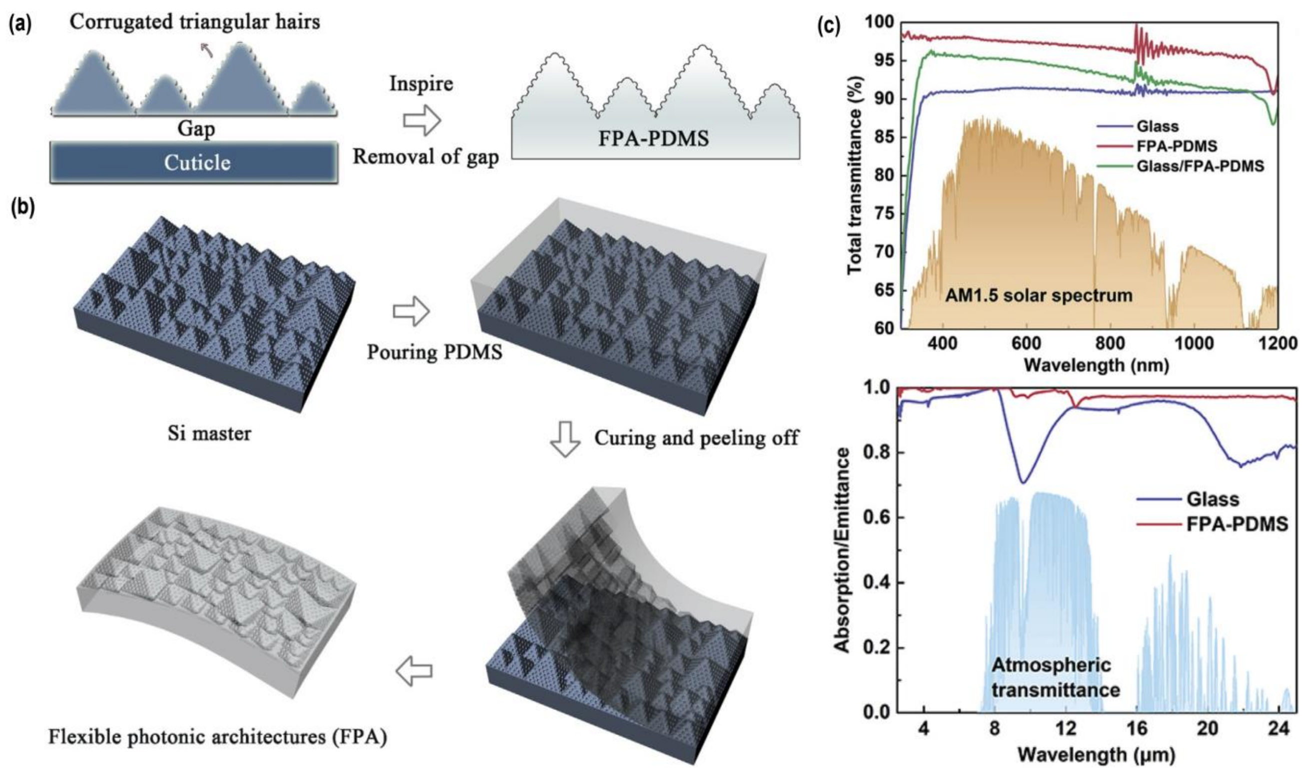

Fig. 8. (a) Conceptual description of flexible photonic architectures (FPAs) inspired by silver ants [77]. (b) Schematic of the preparation of the FPA-PDMS [77]. (c) Measured spectral properties of the bare glass, FPA-PDMS, and FPA-PDMS on glass [77]. (a)–(c) are reprinted with permission from Lin et al., *Sol. Energ. Mat. Sol. C.* 203, 110135 (2019). Copyright 2019 Elsevier.

2.3 Enhancements of sub-bandgap reflection and long-wave thermal radiation simultaneously

Enhancing solar absorption not always improves the PV efficiency. Sub-bandgap solar photons (photons with energy lower than the bandgap) cannot induce photovoltaic conversion but reversely aggravate the thermal load of a solar cell. Therefore, rejecting sub-bandgap solar photons is an effective route to mitigate the thermal loss of the PV module along with radiative cooling and is worth pursuing [81, 82].

However, the strategy of simultaneously enhancing sub-bandgap reflection and long-wave thermal radiation to improve the PV efficiency was not reported until recently Sun et al. [83] proposed an optics-based approach to mitigate the PV self-heating caused by sub-bandgap solar absorption and imperfect thermal emission. The authors hypothetically added a sub-bandgap optical filter atop the PV module to degrade solar absorption in the sub-bandgap spectrum and modified both the top and bottom surfaces of the solar cell to augment radiative cooling. Simulation results suggested that enhancing sub-bandgap reflection and long-wave thermal radiation simultaneously can cool the PV module up to 10 °C and a 0.5 percentage point increase can be realized for the PV efficiency. Unlike Sun et al. [83] who only proposed a hypothetic structure, Li et al. [84] designed a photonic cooler consisted of a multilayer dielectric stack with several sublayers. Each sublayer is composed of Al_2O_3, SiN, TiO_2, SiN, and SiO_2, as shown in Fig. 9. This photonic structure simultaneously enhances sub-bandgap solar reflectance and mid-infrared thermal emission. By putting the photonic cooler atop the glass cover of a crystalline silicon solar cell, the operation temperature of the solar cell can be reduced by 5.7 °C, contributing to an absolute efficiency increment of 0.56%. Zhao et al. [85] also designed a photonic structure consisting of 1D multilayer stack and 2D photonic crystal (see Fig. 10) that reflects most solar radiation in sub-bandgap wavelengths and strongly emits heat to the cold sky, while keeping high solar transmission in the above-bandgap spectrum. The photonic cooler atop the monocrystalline silicon solar cell can help the cell gain a diurnal electricity output of 99.2 W/m^2 and a nocturnal radiative cooling flux up to 128.5 W/m^2, which are correspondingly 6.9% and 30.5% higher than those of a bare cell. An et al. [73] designed a photonic radiative cooler that integrates a multilayer thin-film stack and a SiO_2 grating to reflect sub-bandgap solar radiation and enhance long-wave thermal emission together. By adding this photonic radiative cooler on the bare thin-film crystalline silicon solar cell, the operation temperature of the solar cell can be decreased by over 10 °C, and the PV efficiency can be improved by 0.45%. Li et al. [86] analyzed the effect of selectively utilizing sunlight (named as selective spectral cooling) alone, passive radiative cooling alone, and combined selective spectral and radiative cooling on the performance of a monocrystalline PV module equipped with a hypothetical modified cover. The simulation-based results revealed that, compared to the commercial monocrystalline PV module at AM1.5, the combined selective spectral and radiative cooling approach helps promote the PV efficiency by 4.55% when the ambient temperature and wind velocity are respectively 36 °C and 2 m/s. A list of some PV cooling technologies involving radiative cooling and sub-bandgap reflection enhancements simultaneously is summarized in Table A3.

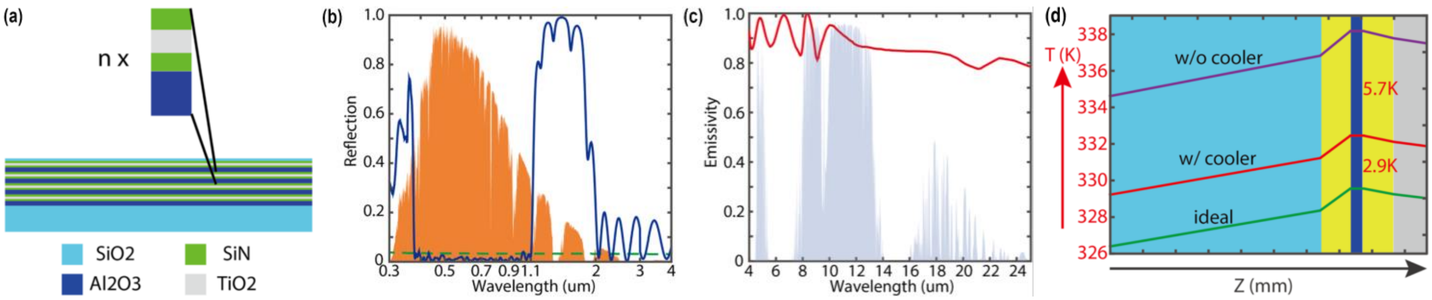

Fig. 9. (a) Schematic of a photonic cooler consisted of a multilayer dielectric stack with several sublayers [84]. (b) Spectral reflection of the photonic cooler with eleven sublayers within 0.3 to 4 μm [84]. (c) Spectral emissivity of the photonic cooler with eleven sublayers within 4 to 25 μm [84]. (d) Predicted temperature distribution along the thickness direction of a solar cell without a photonic cooler (purple), with the designed photonic cooler (red), and with an ideal photonic cooler (green), respectively [84]. (a)–(d) are reprinted with permission from Li et al., *ACS Photonics* 4, 774–782 (2017). Copyright 2017 American Chemical Society.

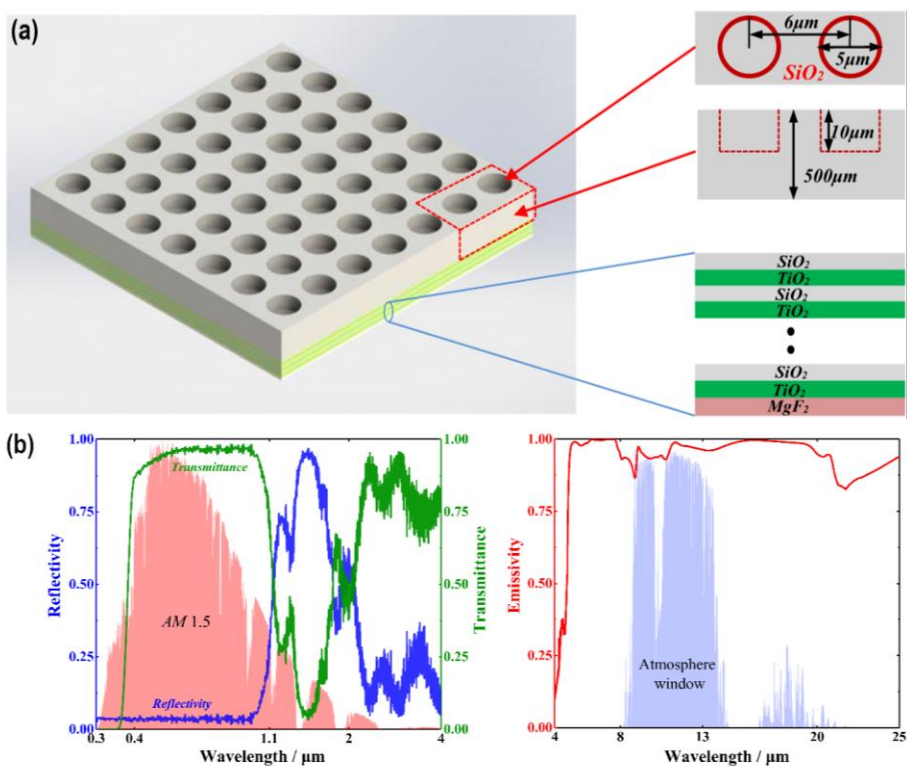

Fig. 10. (a) Schematic of a photonic structure consisted of 1D multilayer stack and 2D photonic crystal [85]. (b) Spectral properties of the photonic structure from 0.3 to 25 μm [85]. (a) and (b) are reproduced with permission from Zhao et al., *Sol. Energ. Mat. Sol. C.* 178, 266–272 (2018). Copyright 2018 Elsevier.

2.4 Combination of daytime solar photovoltaic conversion and nighttime radiative cooling

Conventional solar PV systems can only generate electricity during the daytime when exposed to solar radiation but are generally idle during the nighttime. Despite its main application in solar PV devices being to lower the operating temperature during the daytime, radiative cooling mechanism can be integrated into the PV panel as an additional function to conduct sub-ambient cooling at night, thus extending the operation hours and shortening the payback period of the PV system.

Pei's group introduced the idea of comprehensive utilization of solar photovoltaic conversion and radiative cooling (PV-RC) and conducted a series of investigations on it in recent years [85, 87-90]. The authors designed a building-integrated solar photovoltaic conversion and radiative cooling (BIPV-RC) system employing air as the working medium [87]. By integrating the air-based PV-RC collector into the sun-facing side of the roof and adjusting different openings, the collector can work as a PV panel during the daytime to provide electricity and operate as a radiative cooler during the nighttime for space cooling. Results suggested that the proposed BIPV-RC system can harvest 564.26 MJ/m^2 green electricity and 579.91 MJ/m^2 free cooling energy throughout the year in Hefei, China, corresponding to a 96.96% improvement in total annual energy gain compared to the typical BIPV system. Thereafter, the authors conducted an experimental study on a commercial mono-crystalline silicon PV panel with a moveable low-density polyethylene (LDPE) cover [88]. The LDPE cover was removed in diurnal PV mode to maximize the solar absorption of the PV panel but was added during the nocturnal RC mode to mitigate cooling losses of the panel. The PV-RC system reached an average diurnal electrical efficiency of 12.4% and an average nocturnal ambient-surface temperature gap of 12.7 °C. However, measured data regarding the radiative cooling flux of the hybrid system was unavailable in this preliminary study as no working medium was introduced. Therefore, Zhao et al. [89] designed and fabricated a novel PV-RC collector that can operate in either water- or air-cooling mode. Based on the novel PV-RC collector, the authors established a PV-RC testing system using water as the thermal carrier (see Fig. 11). Experimental results indicated that the daily average PV efficiency and nighttime net RC power of the PV-RC system were respectively 14.9% on a mostly sunny day and 72.9 W/m^2 on a mostly clear night. In addition to integrating daytime solar PV and nighttime RC mechanism into a single collector, Zhao et al. [90] also demonstrated the significance and effectiveness of respectively placing the PV panel and RC collector on the sunward and anti-sunward facing roof to provide electricity and cooling energy for the building sector, delivering a new form of BIPV-RC application. A comparative study among the proposed BIPV-RC system, the typical BIPV and building-integrated radiative cooling (BIRC) systems was carried out and the simulation-based results revealed that the annual total energy gain of the BIPV-RC system is about 79.1% and 16.8% greater than that of the BIPV and BIRC systems, respectively.

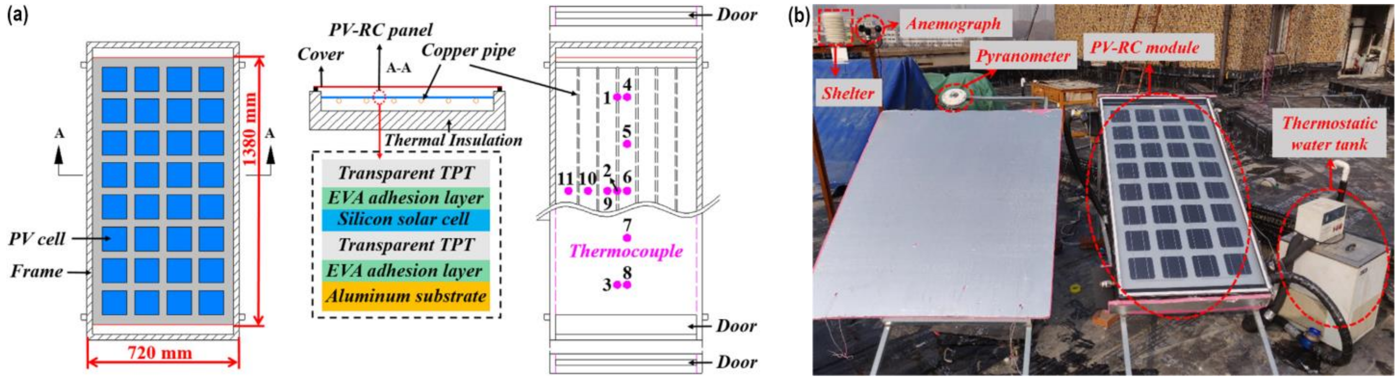

Fig. 11. (a) Schematic of a solar photovoltaic conversion and radiative cooling (PV-RC) collector. The collector can operate in either water- or air-cooling mode [89]. (b) Photo of the PV-RC testing system in water-cooling mode [89]. (a) and (b) are reprinted with permission from Zhao et al., *Appl. Energ.* 252, 113432 (2019). Copyright 2019 Elsevier.

3. Radiative cooling in solar photothermal systems

Solar thermal collecting and radiative cooling harvesting represent quite the opposite approaches to capturing renewable energy from the universe. Solar photothermal conversion (PT) prefers the highest possible spectral absorptivity in the solar spectrum (0.3 to 3 μm) while the lowest possible in the rest wavebands, which leads to the development of solar selective absorbing coatings (SSAC) in solar thermal collectors [91]. However, radiative coolers should exhibit the lowest possible solar absorption if daytime radiative cooling is pursued and requires strong thermal emission outside the solar spectrum, at least in the "atmospheric window" [92].

In most regions worldwide, hot and cold seasons appear alternately, indicating that heating or cooling is required dynamically for situations such as indoor thermal environments. Stand-alone solar collectors and radiative coolers, therefore, may encounter drawbacks in terms of seasonal adaptability. A solar collector (or a solar Trombe wall) may provide low-value even unwished heat in summer, adding extra burdens on the cooling load of buildings [93]; likewise, a roof-mounted radiative cooler tends to exert an undesired cooling effect in winter. Therefore, the comprehensive utilization of solar photothermal conversion and radiative cooling (PT-RC) has been brought out and developed for years to cover the disadvantages associated with the two technologies when applied alone [94, 95]. In this section, the progress of radiative sky cooling in solar photothermal modules and systems is summarized. According to different combination ways, the literature review is classified into four sub-sections: (1) Detached systems, (2) Spectrally non-selective coupled systems, (3) Spectrally selective coupled systems, and (4) Other systems.

3.1 Detached systems

The term "detached" in the present study indicates that the PT and RC systems are applied in the same scenario but spatially separated. Buildings are the main application scenario for hybrid PT-RC systems. A significant portion of heating and cooling loads can be covered by the building-integrated solar photothermal conversion and radiative cooling (BIPT-RC) system. Generally, a typical house with two pitched roofs is situated in a way that one roof points toward while the other away from the sun. While solar thermal collectors are installed at the sunward facing roof, the anti-sunward facing roof is usually idle and can be exploited but has not received much attention. The solar radiation projected onto the anti-sunward facing roof is very low, making it possible for the realization of daytime radiative sky cooling even with materials showing not extremely high solar reflectance [58]. Fig. 12 illustrates a detached PT-RC system using water as the thermal carrier for building energy-saving. The solar collector is mounted on the sunward facing roof to collect heat, and the radiative cooler is placed on the anti-sunward facing roof to dissipate heat to the cold outer space. Water in the hot tank is delivered to the solar collector and extracts heat before it flows back to the tank in sunny daytime. Water in the cold tank is pumped to the radiative cooler and transfers heat to the cooling panel in both daytime and nighttime.

Some early studies demonstrated the combination of the radiative cooling system into the building-integrated solar photothermal conversion (BIPT) system by arranging the radiative coolers on the anti-sunward facing roof. Givoni [96] developed a roof radiation trap to capture solar energy for space heating in winter and night sky cooling for space cooling in summer. The outdoor airflow under a white corrugated metal sheet could be cooled by about 5 °C below the ambient temperature in the radiative cooling mode, but the space heating performance characteristic was not quantitively given in this preliminary study. Parsons and Sharp [97] developed a combined passive PT-RC system for building energy-saving by using separated heating and cooling components. The solar collector is placed at the south-facing façade while the sky radiator is installed at the flat roof. Several heat pipes serve as the heat transfer unit to deliver solar thermal energy during the winter daytime and radiative sky cooling energy during the summer nighttime. Using the weather data of Louisville, Kentucky, simulation results suggested that the highest fraction of energy harvested from the sun and the cold sky reaches 0.707. Li et al. [98] devised a dual-functional apparatus including a pair of rotary actuators or rollers and a thin-film polymer composite that exhibits solar heating and radiative cooling functions side-by-side (see Fig. 13). The dual-mode heat managing device, potentially being the smart dual-mode building envelopes, could reach up to 643.4 W/m^2 of heat flux (with over 93% of solar thermal efficiency) in solar heating mode and up to 71.6 W/m^2 of cooling power in radiative cooling mode. Yoon et al. [99] proposed a hybrid heating, ventilation, and air-conditioning (HVAC) system consisting of a solar collector and a radiative cooler for building energy-saving. Annual performance simulation suggested that, when applied to three different climate regions (Denver, Pheonix, and Los Angeles), the system can save year-round power consumption by about 3% to 29% compared to the radiative cooling-assisted and solar-assisted heat pump systems. A summary of some references regarding the detached PT-RC system is presented in Table A4.

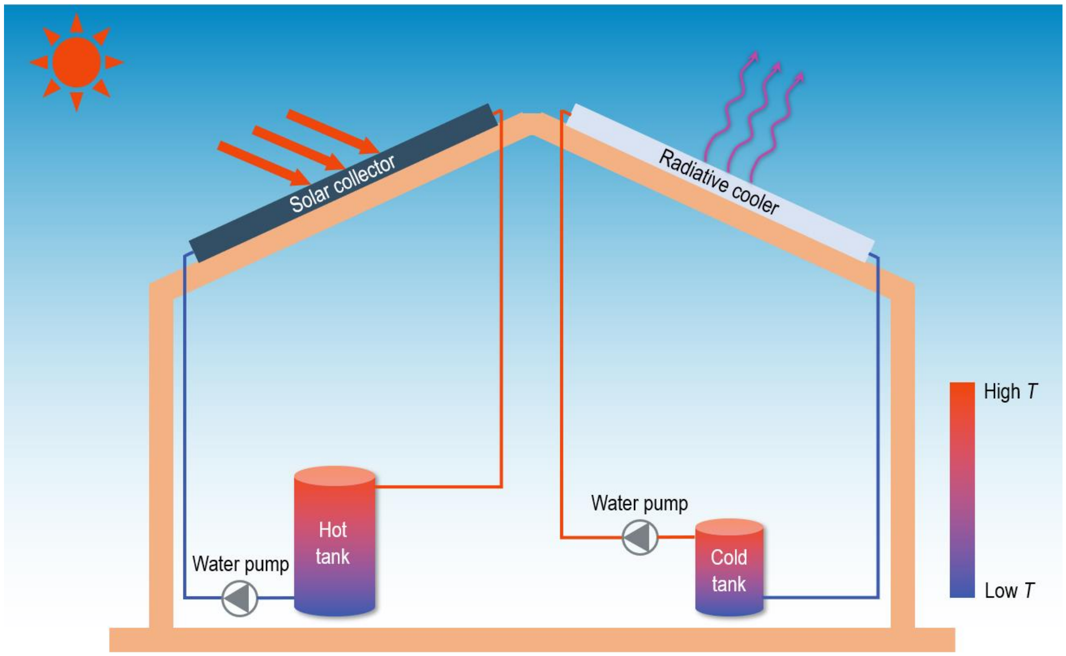

Fig. 12. Schematic of a detached building-integrated solar photothermal conversion and radiative cooling (BIPT-RC) system.

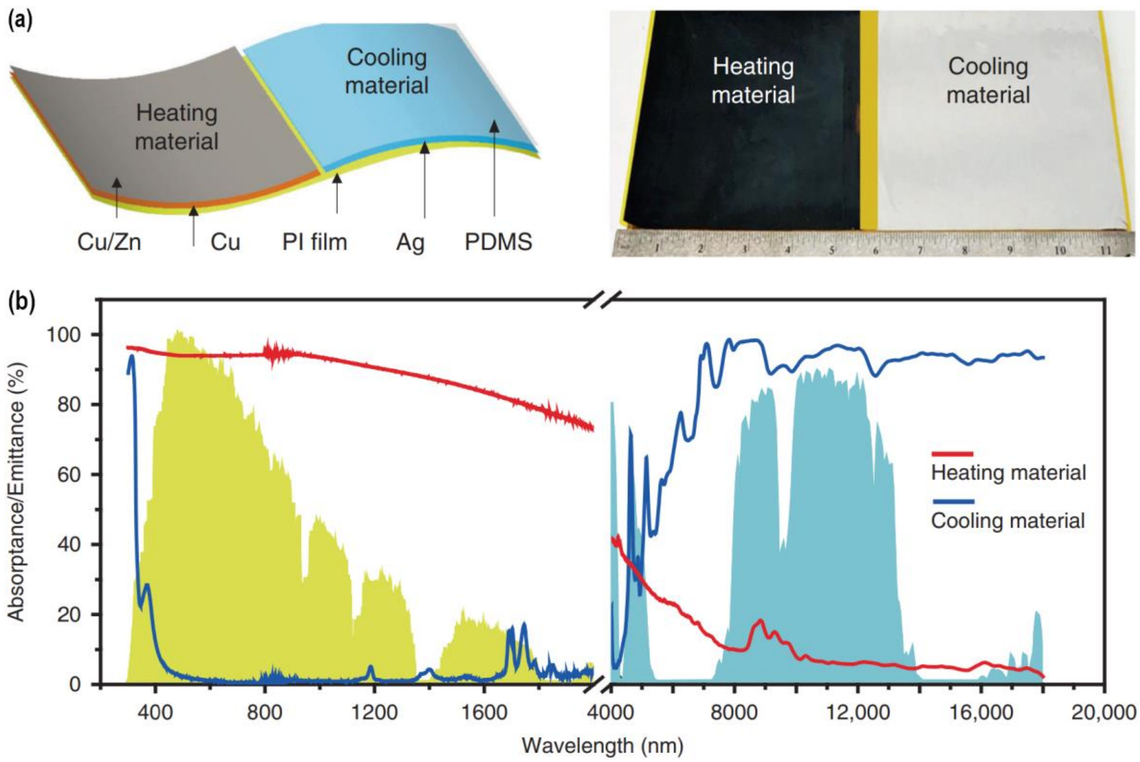

Fig. 13. (a) Schematic and photo of a dual-mode solar heating and radiative cooling material that shows the potential of being smart building envelopes [98]. (b) Spectral absorptivity (emissivity) of the dual-mode heating/cooling material [98]. (a) and (b) are reproduced with permission from Li et al., *Nat. Commun.* 11, 6101 (2020). Copyright 2020 Springer Nature Limited.

3.2 Spectrally non-selective coupled systems

Though the detached PT-RC system can realize heat and cooling energy supply together, the system itself shows inherent drawbacks such as high initial cost and system complexity. Stimulated by these problems, radiative cooling has been regulated to be directly integrated into existing solar thermal collectors. The most common way of combining radiative cooling and solar heating in a single device is replacing the solar absorber of a flat-plate solar collector with a spectral non-selectively absorber/emitter that shows high absorptance and emissivity throughout the ultraviolet, visible light, and infrared spectra. Besides, as the glazing cover widely used in solar collectors will block the infrared thermal emission from the absorber/emitter to the sky and thus severely deteriorate the radiative cooling performance, many researchers attempted the reconstruction by removing the glazing cover from the solar collector and topping the solar absorbing panel with high-emissivity coatings to achieve the nighttime cooling purpose [100-107].

Erell and Etzion [100] modified two commercial flat-plate solar collectors to achieve nighttime sky cooling by removing the glazing cover and painting the panel with a white coating. Experimental results revealed that an average radiative-convective cooling flux of 80 W/m^2 was observed over an eight-hour testing period. Afterward, in another study, the authors experimentally found that this modified collector could still realize daytime solar heating performance, with a mean heating flux of 370 W/m^2 on a sunny winter day in Sde-Boker, Israel [101]. Hosseinzadeh and Taherian [105] employed two uncovered solar collectors with a galvanized iron panel to harvest cooling energy in a humid Iran area. Experimental results indicated that the sum of radiative and convective cooling fluxes ranged from 23 to 52 W/m^2. Vall et al. [106] proposed a radiative collector and emitter with a movable cover and an assumed blackbody absorber/emitter and numerically evaluated its application potential in buildings located in different climate regions. Results suggested that the device, when applied to single-family, multi-family, and hotel buildings, can cover at least 25% of cooling load and 75% of domestic hot water demand in five selected cities (San Francisco, Cape Town, Johannesburg, London, and Ottawa).

Lee et al. [108, 109] conducted a series of researches on a house containing a central air circulation system that uses a roof ventilation layer and a PCM unit. The roof ventilation layer with the external surface galvanized was employed to act as a solar heater in winter daytime and as a radiative cooler in summer nighttime, while the PCM unit stored heat or cooling energy to regulate the indoor air temperature and reduce the peak load of the building. Results indicated that the proposed renewable energy system realized a total sensible heat reduction of around 28% compared with the conventional HVAC system. In addition to carrying out solar thermal collection in winter daytime and radiative sky cooling in summer nighttime, Lee et al. [110] further demonstrated that the system could perform passive dehumidification in summer daytime to reduce the latent heat load and to control indoor humidity (see Fig. 14). Since the ambient relative humidity is generally higher during nighttime than the preceding daytime hours, the ambient air is often difficult to be cooled remarkably, limited by the latent heat release. Therefore, solutions that can pre-dehumidify the ambient air before the radiative cooling process will be appreciated. The desiccant bed is proved to be such a potential approach to enhance the nocturnal radiative cooling performance. Ali [111] proposed a desiccant enhanced diurnal solar thermal collecting and nocturnal radiative cooling system for air conditioning in hot arid areas of Upper Egypt. In the radiative cooling mode, humid inlet airflow is firstly dehumidified by the desiccant bed and then cooled down by the absorber/radiator plate and finally become cold dry air at the outlet. The outlet air temperature is lower than the ambient temperature by 5.5 to 7 °C, with the relative humidity below 40% at an air mass flow rate of 0.64 m^3/min. Bokor et al. [112] investigated the radiative cooling potential of an unglazed transpired solar collector equipped with a spectrally non-selective absorber. Experimental results indicated that a 5 m^2 setup could cool the ambient air by up to 4 °C, with an average cooling power density of 34.6 W/m^2 during a multi-night test at Edirne, Turkey.

The solid absorber/radiator can also directly act as the building envelope, as demonstrated by Wang et al. [113, 114]. The authors constructed a hybrid system featured an uncovered radiant panel with both heating and cooling functions. Experimental results indicated that a maximum daily average solar thermal efficiency of 61% and an average cooling capacity of 50 W/m^2 were realized [113]. In a following study, the authors further developed the uncovered PT-RC panel and integrated it into the sunward facing façade to obtain hot water during the daytime and cold water at night. Two panel coatings with different solar absorptivity and long-wave emissivity were applied as the absorbing/radiating material. Results showed that, although an average cooling flux of 30 W/m^2 was obtained in January, the average solar thermal efficiency of the two panels were only 39% and 27% due to the uncovered structure and poor spectral selectivity of the coatings.

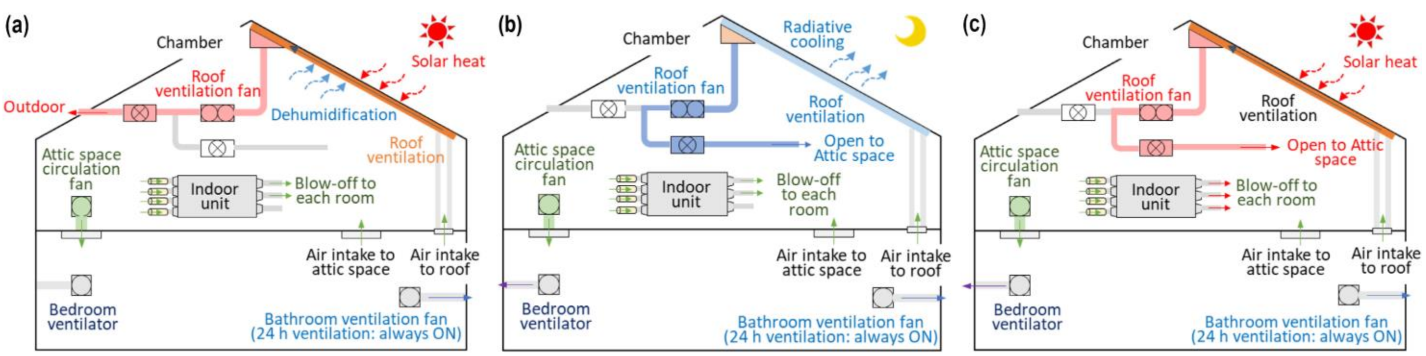

Fig. 14. Schematic of an energy-efficient house using the roof ventilation layer to conduct (a) passive dehumidification in summer daytime [110], (b) radiative cooling and dehumidification by adsorption in summer nighttime [110], and (c) solar thermal collection in winter daytime [110]. (a)–(c) are reproduced with permission from Lee et al., *Energ. Buildings* 195, 139–148 (2019). Copyright 2019 Elsevier.

In general, the modified uncovered solar collectors will show good cooling capacity when the panel temperature is higher than the ambient air due to additional convective heat dissipation. However, two noticeable drawbacks should not be overlooked. First, truly useful "cooling energy" can possibly be obtained only when the panel temperature is lower than that of the surroundings, in which situation the non-covered design will induce large convective cooling loss and thus lead to poor cooling performance. Second, since the panel coatings of these modified uncovered solar collectors show high infrared emissivity, their solar thermal collecting efficiency will be low due to substantial infrared radiative heat loss, associated with inevitable convective heat loss caused by the non-covered structure. Therefore, an uncovered PT-RC collector with spectrally non-selective high-emissivity coating does not seem to be a good candidate for the comprehensive utilization of solar thermal collecting and radiative cooling.

Replacing the glazing cover with an infrared transparent cover such as polyethylene film can significantly suppress convective heat/cooling loss but marginally affect the radiative cooling performance [115, 116]. By employing a low-density polyethylene film as the transparent cover and a cheap commercial black acrylic paint as the panel coating, Hu et al. [115] deployed a hybrid PT-RC collector. Experimental results revealed that this collector showed a solar thermal efficiency of 63.0% at zero-reduced temperature, indicating better solar heating performance than that of the uncovered one [101]. Besides, the net radiative cooling flux of the dual-functional prototype was recorded at 55.1 W/m^2. However, compared to the conventional solar collector [117] which is generally equipped with the SSAC, the solar heating performance of this spectrally non-selective collector is still much lower due to its high long-wave emissivity. Table A5 presents a list of some spectrally non-selective coupled PT-RC systems.

3.3 Spectrally selective coupled systems

The fundamental reason for the inferior solar thermal performance of the hybrid PT-RC apparatus is the spectral conflict between the PT and RC schemes. As previously discussed, an ideal solar collector should possess emissivity as low as possible excluding the solar spectrum to reduce radiative heat loss, while a perfect sky radiator should exhibit the highest possible emissivity at least in the “atmospheric window”. Therefore, reducing daytime radiative heat loss while keeping good nighttime radiative cooling performance is a challenge for integrated PT-RC collectors. Matsuta et al. [118] introduced the concept of spectrally selective coupled PT-RC to alleviate the penalty on solar thermal performance. The authors prepared a solar collector-sky radiator using a spectrally selective surface for water heating at daytime and water cooling at night, which achieved a maximum net heating flux of 610 W/m^2 and a cooling density of 51 W/m^2 during the experiments.

Fundamentally, a spectrally selective coupled PT-RC surface shows high spectral absorptivity (emissivity) in the solar spectrum and “atmospheric window” to guarantee acceptable daytime thermal efficiency and nighttime cooling flux. Moreover, the surface has low spectral absorptivity in bands excluding the solar spectrum and “atmospheric window” to decrease diurnal radiative heating loss and nocturnal radiative cooling loss. An ideal spectrally selective coupled PT-RC panel, thereby, should exhibit unity absorptivity (emissivity) in the solar spectrum and “atmospheric window” while zero in the rest bands (see Fig. 15). Hu et al. [119-124] systematically conducted a series of investigations concerning the integration of radiative cooling into solar thermal collecting panels by applying a spectrally selective coating. By topping the titanium-based SSAC with polyethylene terephthalate film, a spectrally selective surface (named as “TPET surface”) was tri-manufactured for diurnal solar heating and nocturnal radiative cooling [119]. The TPET surface shows distinct spectral selectivity, with an average absorptivity of 0.92 in the solar spectrum and an average emissivity of 0.8 in the "atmospheric window", while a relatively low absorptivity/emissivity (0.55) in the rest bands. Thereafter, Hu et al. [120] proposed and fabricated a water-based PT-RC collector by employing the TPET surface as the absorber/emitter. The photothermal efficiency and radiative cooling flux of the hybrid collector at zero-reduced temperature were respectively 62.7% and 50.3 W/m^2 and decreased to 45.9% and 36.6 W/m^2 if ambient air was employed as the working fluid [121]. It is easy to understand that the water-based PT-RC system shows greater solar thermal efficiency and radiative cooling flux than the air-based one due to the different heat transfer properties between water and air. Yet, the air-based system has some evident advantages over the water-based one in terms of simplicity, cost, lifespan, anti-freezing, etc.

In a following study, by applying the spectrally selective TPET surface reported in Hu et al.'s work [119], Nwaji et al. [125] numerically investigated a water-based solar collector/nocturnal radiator in five Nigerian cities with different climate conditions. Prediction results suggested that the water can be heated up to 45 °C above the ambient temperature during the solar heating mode and cooled down to at least 5 °C below the ambient temperature during the radiative cooling mode in all the five cities. Zhao et al. [124] designed a spectrally selective PT-RC surface consisted of a layer of PDMS, two layers of Ni-Al_2O_3 mixing material, and an aluminum substrate (see Fig. 16). The multilayer surface structure shows a strong solar absorptivity (0.92) and a high mid-infrared emissivity (0.84) in the "atmospheric window", enabling itself to be heated to 79.1 °C above the ambient temperature during the daytime and be cooled to 10 °C below the ambient temperature at night. Table A6 gives a list of some spectrally selective coupled PT-RC systems.

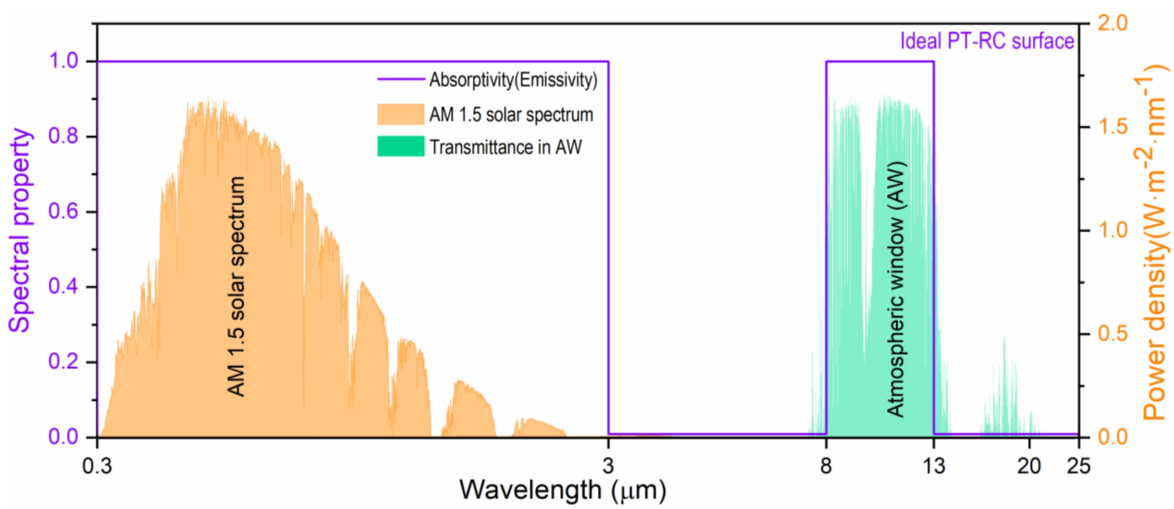

Fig. 15. Spectral features of the ideal spectrally selective coupled solar photothermal conversion and radiative cooling (PT-RC) surface.

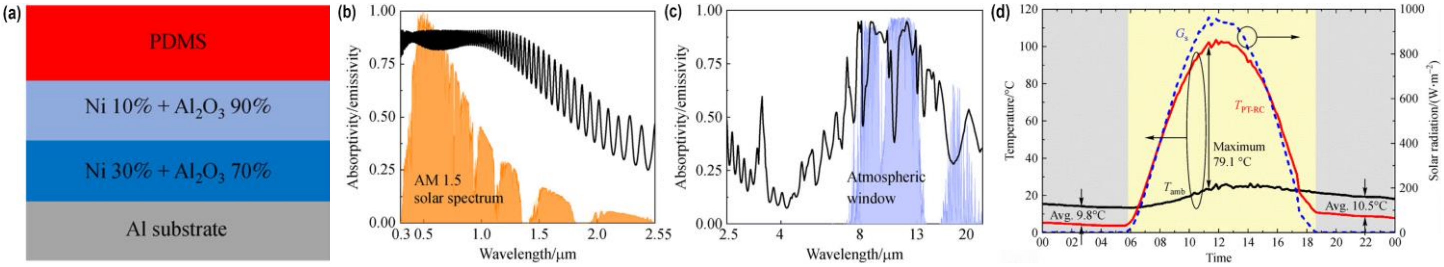

Fig. 16. (a) Schematic of a spectrally selective solar photothermal conversion and radiative cooling (PT-RC) surface consisted of a layer of PDMS, two layers of Ni-Al_2O_3 mixing material, and an aluminum substrate [124]. (b) Spectral absorptivity (emissivity) of the surface within the solar spectrum [124]. (c) Spectral absorptivity (emissivity) of the surface from 2.5 to 25 μm [124]. (d) Simulated surface temperature through 24 consecutive hours, with the ambient temperature and solar irradiance plotted for reference [124]. (a)–(d) are reproduced with permission from Zhao et al., *Front. Energy.*, 1–7 (2020). Copyright Higher Education Press 2020.

3.4 Other systems

Except for those detached, spectrally non-selective coupled, and spectrally selective coupled PT-RC systems discussed above, there have been a few other systems realizing combined solar thermal collection and radiative sky cooling in recent years, as summarized in Table A7.

Water can also be employed directly as the absorber/radiator due to its high solar absorptance and long-wave emissivity. Sameti and Kasaeian [126] proposed a water wall that acts as a dual-functional (solar heating and radiative cooling) system to passively regulate the indoor temperature profiles through natural convection and radiation. A MATLAB program was established to evaluate the monthly and annual solar and radiative cooling fractions, auxiliary heating and cooling demands as well as the unwanted heat gain during heating months. Results reveal that the hybrid system can cover 54% of annual heating demand and 53% of annual cooling demand. Vall et al. [127, 128] proposed a black painted radiative collector and emitter, in which a glass screen was employed as the cover in the solar heating mode but was replaced by a polyethylene film in the radiative cooling mode. Experimental results suggested that average solar thermal efficiency up to 49% and radiative cooling efficiency of 32% were achieved respectively. However, the required cover replacement during the mode switching is somewhat impractical for real-world applications. Noticing that the glazing cover in solar thermal collectors shows high infrared emissivity that can be a night sky radiator, Hu et al. [129] modified a flat-plate solar air heater to achieve attached radiative cooling function. A polyethylene film was arranged above the glazing cover to act as the second cover of this “double-covered” PT-RC module. The air duct was set between the glazing cover and selective solar absorber, letting the air stream extracts heat from the solar absorber during the daytime and throw heat to the glazing cover during the nighttime (see Fig. 17). The most merit of this structure is that the diurnal solar heating performance will not be affected by radiative cooling as the heating and cooling components (solar selective absorber and glazing cover, respectively) are separated. Experimental results even demonstrated that the double-covered PT-RC module performed better than the conventional solar heater in heat collection attributed to the addition of the second cover, evidenced by a 4.6 °C higher stagnation temperature of the solar absorber.

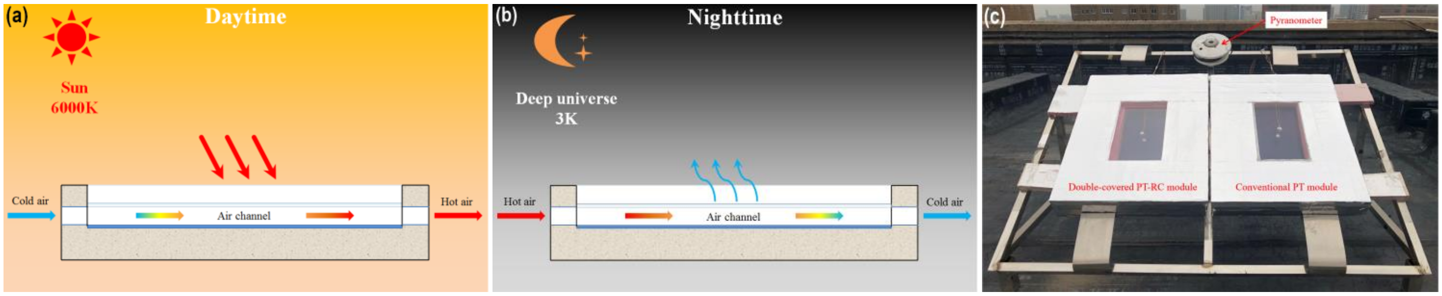

Fig. 17. (a) Schematic of a double-covered solar photothermal conversion and radiative cooling (PT-RC) module working as an air heater [129]. (b) Schematic of the double-covered PT-RC module operating as an air cooler [129]. (c) Experimental rig of the double-covered PT-RC module (left) and a parallel conventional solar photothermal conversion (PT) module (right) [129]. (a)–(c) are reproduced with permission from Hu et al., *Sol. Energ.* 197, 332–343 (2020). Copyright 2020 International Solar Energy Society. Published by Elsevier.

Considering that either the radiative cooler or the solar heater only uses one side (the sky-facing surface) to harvest energy, some researchers proposed the idea of integrating solar heating and radiative cooling by setting one side as a radiative emitter while the opposite side a solar absorber [130-133]. Such a dual-side structure can avoid the spectral incompatibility between solar heating and radiative cooling mechanisms. It can output heat or coldness according to the energy demand in different seasons. Yue et al. [130] prepared a robust Janus fibrous membrane with a tri-layer structure composed of ZnO nanorods array-coated cellulose, ultralong MnO_2 nanowires, and Ag nanowires. The ZnO-based side acts as a radiative cooling surface that shows a high solar reflectance (0.85) and a high long-wave emissivity (0.87) and will face the sky in hot environments. The Ag-based side behaves as a solar absorber which presents relatively high solar absorptivity (0.59) and high long-wave reflectance (0.43) and will face the sun when heat is required. Such a Janus membrane may potentially serve as building blocks and effectively tune the indoor thermal environment under dynamic weather conditions. Compared to a bare house wall, the temperature of the Janus membrane was about 5.8 °C higher while around 9.6 °C lower after 180 min of simulated solar radiation exposure for the Ag- and ZnO-based side, respectively. Liu et al. [131] designed a PT-RC module with one side coated by solar absorbing materials and the other side covered by porous cooling materials, as shown in Fig. 18. Experimental results revealed that the indoor air could be cooled to about 6.5 °C below the ambient temperature in low latitude areas in summer and reached 25 °C in winter daytime without additional heat supply. Song et al. [132] designed and fabricated a Janus membrane with switchable functions between solar heating and radiative cooling. The heating side showed a solar absorptivity of 74.1% and thermal emissivity of 10.5%, while the cooling side reached a solar absorptivity of 9.4% and thermal emissivity of 89.2%. Such spectral profile allowed the Janus membrane to heat up an inner space by 12.5 °C in the heating mode and cool down the inner space by 10.9 °C in the cooling mode. Hu et al. [133] proposed a bifacial PT-RC module capable of flexibly switching between heating and cooling modes to realize smart thermal management. Simulation results suggested that, provided the panel temperature equals the ambient temperature at 30 °C, the bifacial module reaches a solar thermal efficiency of 83.3% when the solar irradiance is 1000 W/m^2 in the heating mode and a net radiative cooling power of 69.9 W/m^2 in the cooling mode.

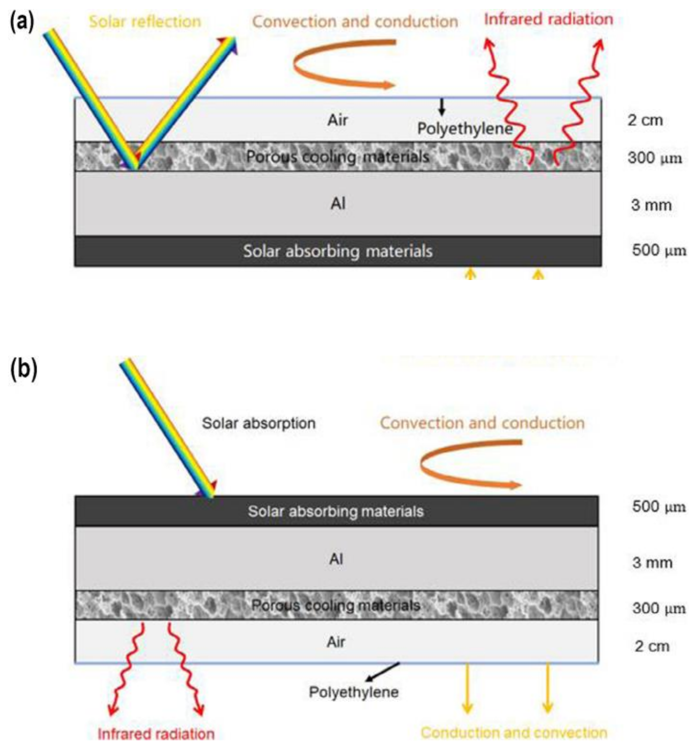

Fig. 18. Schematic of a solar photothermal conversion and radiative cooling (PT-RC) module with one side coated by solar absorbing materials and the other side covered by porous cooling materials [131]. (a) The cooling side is skyward in the radiative cooling mode. (b) The heating side faces the sky in the solar heating mode. (a) and (b) are reproduced with permission from Liu et al., *Energ. Convers. Manage.* 205, 112395 (2020). Copyright 2019 Elsevier.

Energy demands (heat and cooling energy) in the building sector are regularly changing throughout the year in most regions across the world. However, the spectral properties for those spectral coupled PT-RC surfaces are generally static, which may cause mismatches between the energy supply and demand for the BIPT-RC system. If a PT-RC module can be self-regulated in spectral properties according to the outdoor thermal environment, it will be more attractive to building energy-saving. Conceptually, a spectrally self-regulating PT-RC surface behaves as a solar absorber with high solar absorption and low long-wave thermal radiation in the solar heating mode, while switches to a radiative cooler with low solar absorption and high long-wave thermal radiation in the radiative cooling mode, as shown in Fig. 19. The latest micro/nano coating technology may pave the way for realizing the spectrally self-regulating PT-RC application.

Vanadium dioxide (VO_2) is a common thermochromic phase-change material that shows the potential of passively regulating the spectral property depending on temperature [134]. VO_2 shows high transmittance at infrared wavelengths when its temperature is below the phase-transition temperature, while presents high reflectance when the temperature exceeds the phase-transition temperature. This switchable spectral response of VO_2 has been employed to self-tune the spectral profile of radiative coolers [135, 136]. Noticing that a typical radiative cooler will still produce unwanted cooling energy on cold days, while a conventional solar heater will elevate undesirable cooling load on hot days, Kort-Kamp et al. [137] proposed a nanophotonic passive radiative thermostat based on VO_2, as shown in Fig. 20. The proposed multilayered thermostat, consisted of a thick Ag substrate and alternating layers of TiO_2, VO_2, and ZnSe, is capable of self-adjusting its spectral properties (i.e., absorptivity in the solar spectrum and emissivity in the mid-infrared band) to limit the temperature difference between itself and the ambient air within a desired and moderated range. Simulated results suggested that, when the phase-transition temperature is 17 °C, the thermostat reaches an equilibrium temperature of 6 °C below the midday ambient temperature in summer and 11 °C above in winter. Peng et al. [138] designed and prepared a smart thermal management textile by combining VO_2 nanoparticles and Ag strips on a polyester (PET) substrate. This well-designed VO_2/Ag-PET structure is transparent to near-infrared (NIR) light at a low temperature (30 °C) to keep human body warm, while reversibly reflective at a high temperature (90 °C) to cool human body. Simulated tests revealed that the VO_2/Ag-PET textile could lower the inner-room temperature by about 13.9 °C under intense solar irradiance.

Excepted for the VO_2-involved designs, a few other structures and innovations have also demonstrated the feasibility of self-regulating PT-RC. Similar to the idea proposed in Ref. [137], Wang et al. [139] developed a compound meta-surface comprising small and large cross resonators, enabling the surface to realize self-adaptive PT-RC in one system. The structure exhibits strong solar absorption and weak "atmospheric window" emission at low ambient temperature (25 °C) to keep itself warm, while presents the opposite property at high ambient temperature (35 °C) to keep itself cool. Mandal et al. [140] prepared optical switchable porous polymer coatings (PPCs) whose optical transmittance changes upon reversible wetting with common liquids such as alcohol or water. The proposed PPCs can act as a platform for optical management from the solar spectrum to the far-infrared wavelengths, indicating that it is suitable for combining solar heating and radiative cooling with a flexible mode-switching strategy. By employing the polytetrafluoroethene PPC as the adjustable roof, switchable sub-ambient radiative cooling by about 3.2 °C in dry state and above-ambient solar heating by 21.4 °C in wet state were experimentally demonstrated under high-level solar irradiance. This attractive dynamic thermo-regulation function indicates the application potential of PPC-based switchable devices in buildings, vehicles, and water tanks in changing daily or seasonal environments.

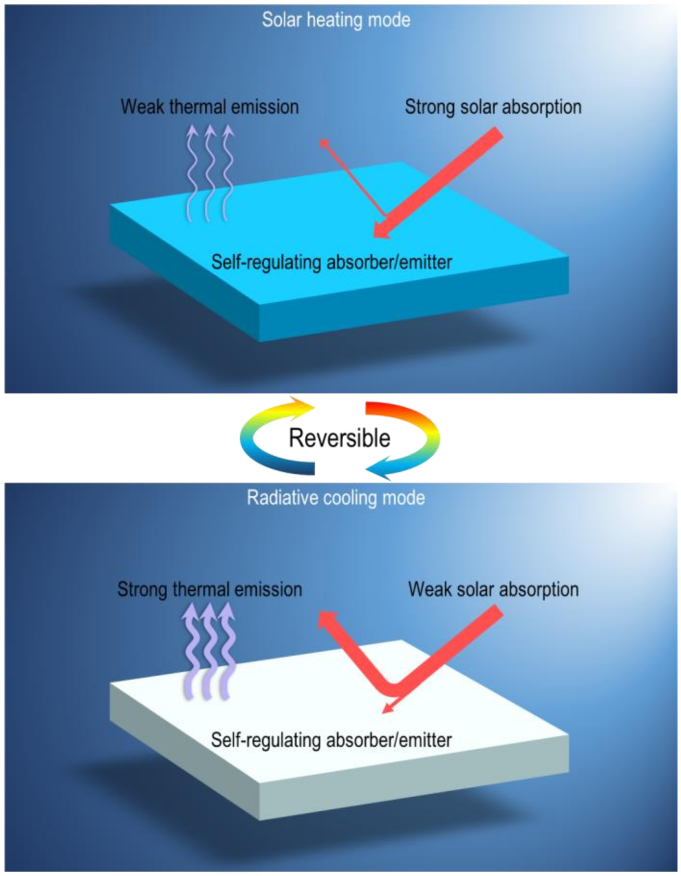

Fig. 19. Conceptual design of the spectrally self-regulating solar photothermal conversion and radiative cooling (PT-RC).

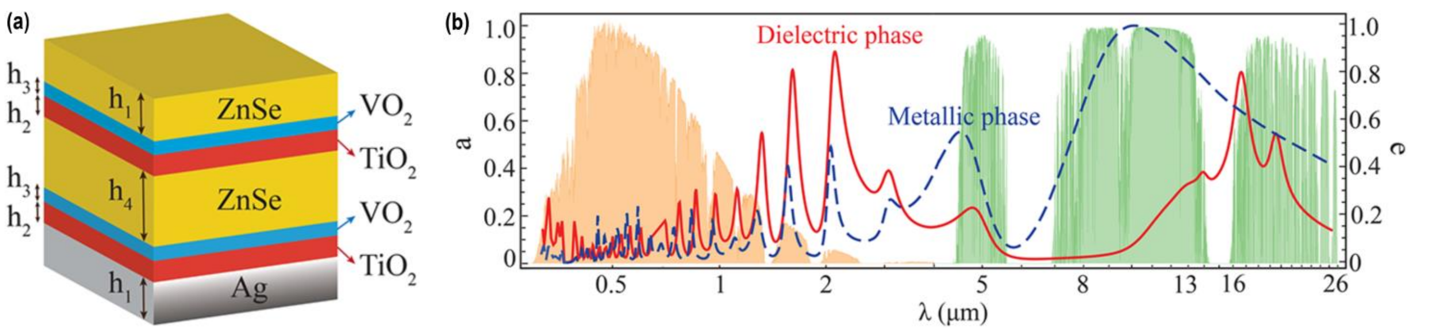

Fig. 20. (a) Schematic of a nanophotonic passive radiative thermostat consisted of a thick Ag substrate and alternating layers of TiO_2, VO_2, and ZnSe [137]. (b) Spectral properties of the radiative thermostat in dielectric and metallic phases, respectively [137]. (a) and (b) are reprinted with permission from Kort-Kamp et al., *ACS Photonics* 5, 4554–4560 (2018). Copyright 2018 American Chemical Society.

Considering that radiative cooling exploits the mid-infrared wavelength that is totally different from the solar spectrum, Chen et al. [141] experimentally demonstrated the idea of simultaneously collecting heat from the sun and gathering coldness from outer space by using a device where a mid-infrared transparent solar absorber is arranged above a radiative sky cooler (see Fig. 21). The solar absorber, an undoped germanium wafer with a double-sided antireflection coating, could be heated to 24.4 °C above the ambient temperature. In contrast, the radiative sky cooler placed in a vacuum chamber could be cooled to 28.9 °C below the ambient temperature when a shading device was attached. In a following study, Zhou et al. [142] demonstrated hybrid concentrated radiative cooling and solar heating in a single system to achieve daytime solar heating and radiative cooling simultaneously. The system consisted of a central radiative cooler partly surrounded by a V-shaped solar absorption mirror. The radiative cooler realized a local cooling power density of 273.3 W/m^2 in a laboratory environment and a stagnation temperature of 14 °C below the ambient temperature in an outdoor condition.

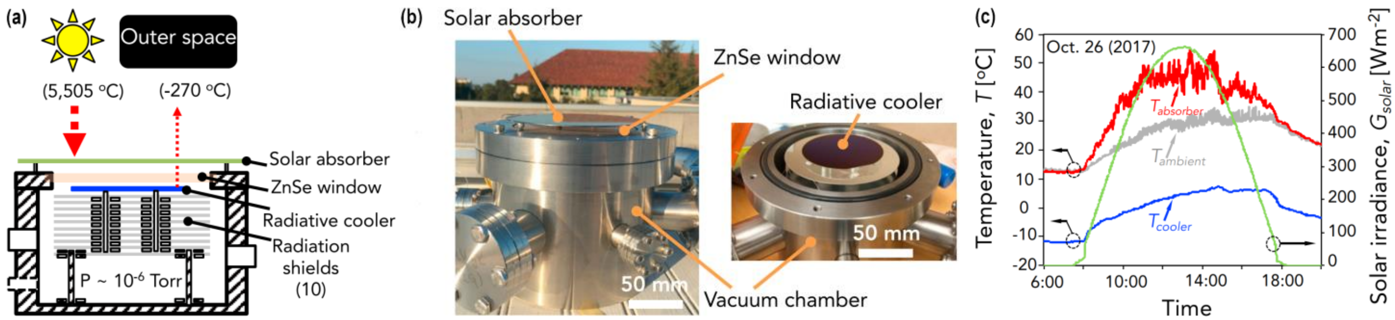

Fig. 21. (a) A vacuumed configuration simultaneously collects heat from the sun and gathers coldness from outer space using a mid-infrared transparent solar absorber and a radiative cooler [141]. (b) Photo of the in-situ experimental setup [141]. (c) Measured solar absorber temperatures and radiative cooler compared to the ambient temperature through a period of 14 consecutive hours [141]. (a)–(c) are reproduced with permission from Chen et al., *Joule* 3, 101–110 (2019). Copyright 2018 Elsevier.

4. Radiative cooling in solar photovoltaic/thermal systems

Solar photovoltaic conversion and thermal collection and are the dominating technologies of solar energy utilization. However, the combined photovoltaic/thermal conversion (PV/T, PV-PT) technology is expected to become popular due to its high overall efficiency and dual-function [45]. The integration of radiative sky cooling into a PV-PT collector or system can further contribute to such merits by adding a night sky cooling function. The concept of comprehensive utilization of solar photovoltaic conversion, photothermal conversion, and radiative cooling (PV-PT-RC), as shown in Fig. 22, is that simultaneously generating electricity and collecting heat by fully exploiting solar energy lies in the entire solar spectrum during the daytime, and gathering cooling energy via sending waste heat to outer space during the nighttime [53, 143, 144]. Electricity, heat, and cooling energy are required on many occasions, such as buildings, agriculture, and vehicles. Take buildings in most regions as an example, electricity and hot water are needed throughout the year, space heating is required in winter, and space cooling is necessary for summer, making the hybrid PV-PT-RC collector/system attractive for building energy-saving applications.

In recent years, the comprehensive utilization of PV-PT-RC technology has been proposed and demonstrated to pave the way for developing Zero Energy Buildings. This section outlines the development of the combination of radiative sky cooling into solar PV-PT collectors and systems. According to the difference in working mediums, the hybrid PV-PT-RC system can be divided into three types: (1) Air-based systems, (2) Water-based systems, and (3) Heat pump-based systems.

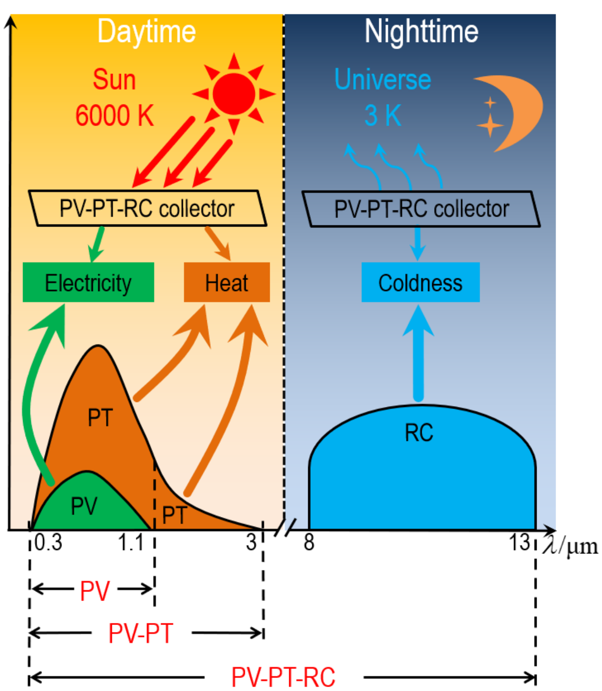

Fig. 22. Schematic of the comprehensive utilization of solar photovoltaic conversion, photothermal conversion, and radiative cooling (PV-PT-RC). The spectral response range of typical crystalline silicon solar cells (0.3 to 1.1 μm) is exemplified.

4.1 Air-based systems

Air-based PV-PT-RC systems are integrated into building envelopes to directly supply hot air for space heating and cold air for space cooling, along with electricity. Considering that the heat capacity of air is too low to effectively and consecutively regulate the indoor thermal environment, additional mediums such as a PCM unit are usually introduced as the thermal energy storage to temporally store the low-grade thermal energy collected from the PV-PT-RC module and to release it later for air conditioning.

Lin et al. [145] put forward a PCM-enhanced ceiling ventilation system equipped with PV-PT-RC collectors. The PV-PT-RC collector in this study is modified from the roof-mounted PV panel. The upper encapsulating material, usually a glazing cover, shows a high infrared emissivity which caters to the spectral requirement of radiative cooling at night. An air channel is arranged between the PV panel and insulation layer to guide the ambient air or indoor air. The ambient air extracts accumulated heat from the PV panel in the daytime heating mode, while the indoor air dissipates heat to the PV panel in the nighttime cooling mode. Also, two layers of PCM with an air channel are integrated onto the roof as a component of the insulating layer to increase the local thermal mass. Simulation results derived from the TRNSYS software indicated that, with a constant airflow rate of 500 kg/h in the air channel, the electrical and thermal efficiencies of the PV-PT-RC collector are respectively 8.31% and 12.5% in winter case and the average temperature decrement of the ambient air flowing through the collector is 2.4 °C in summer nighttime case. It is worth noting that, despite the poor heat-transfer capability of air and PV efficiency of particular solar cells, the PT efficiency and RC performance of this uncovered PV-PT-RC collector are at a very low level compared to other PV/T collectors or RC devices with a convection-suppression cover [23, 121]. In two subsequent studies, Fiorentini et al. [146, 147] proposed a novel HVAC system consisted of an air-based PV-PT-RC collector and a PCM storage unit integrated with a reverse cycle heat pump. The PV-PT-RC collector can heat or cool ambient air which is later supplied either directly to the room or to the PCM storage unit which acts as a thermal regulator to make the energy supply match the dynamic energy demand better. The experimental electrical and thermal efficiencies of this PV-PT-RC collector were respectively 8.2% and 9.0% in Datong in summer daytime. Further simulation results indicated that the cooling energy reaches 1.5 kW when the airflow rate is 300 L/s in Sydney in summer nighttime.

4.2 Water-based systems

Compared to very few studies that employed air as the working medium of the PV-PT-RC system, much more works paid attention to the water-based PV-PT-RC system given that water, as the thermal carrier, shows better heat transfer performance [148-163]. However, the water temperature at the outlet of the PV-PT-RC collector in an opened system can hardly be heated up or cooled down to effective levels due to its large thermal capacity. Therefore, the water-based PV-PT-RC system is usually a closed system containing a circulating water tank. Water in the tank will be circulated in the closed system to reach the desired temperature before being sent to the end-users, though the incorporation of such a storage tank also brings side effect of adding complexity to the system.

The building sector is the main application scenario of the water-based PV-PT-RC system as well. Like the detached PT-RC systems introduced in Section 3.1, Saitoh and Fujino [148, 149] proposed a detached water-based PV-PT-RC system to realize an advanced energy-efficient house with directionally opposite roofs. Results suggested that water in the water tank reached 65 °C in the heating season while decreased to 10 °C by the radiative coolers alone in the cooling season. In general, the so-called ‘HARBEMAN’ house consumes only 1/6 of fossil energy compared with the conventional house.

Eicker and Dalibard [150] firstly demonstrated that the night sky cooling effect could be achieved using an uncovered PV/T collector, in which a layer of glass serves as not only the encapsulating material of PV cells but also the radiative cooler. An array of such uncovered water-based PV/T modules were integrated into the roof of a zero-energy building named “Home+” located in Madrid, Spain. Experimental radiative-convective cooling flux ranged from 60 to 65 W m^2 when the collector connected with a circulating water tank and was around 40 to 45 W m^2 when the energy was directly used to cool a ceiling. Water-based PV-PT-RC collectors can also be integrated with PCM to provide electricity, heat, and cooling energy in the building sector. Bourdakis et al. [156] proposed a PCM ceiling panel for daytime space cooling. The PCM unit was discharged via nighttime ventilation and night sky cooling from water-based PV-PT-RC collectors and released coldness during the daytime for indoor thermal environment regulation. The experimental electrical, water-heating, and water-cooling fluxes of the PV-PT-RC panel in different cases recorded around 28.0 to 63.2 W/m^2, 27 to 72.2 W/m^2, and 56.3 to 82.1 W/m^2, respectively. Gürlich et al. [158] conducted a basic economic analysis on a closed, uncovered, and water-based PV-PT-RC system (see Fig. 23) in three European cities representing different energy demands, climate features, and energy prices. The trigeneration system can contribute 51%, 18%, and 63% of annual electricity consumption and 47%, 29%, and 32% of domestic hot water demand in Almada, Bologna, and Nottingham. Besides, the system can cover 3% to 9 % of cooling load in the three cities if the cooling water with a temperature of 16 °C is required, and the cooling load coverage increases to up to 29 % if a higher cooling water temperature of 20 °C is set. Following Eicker and Dalibard’s work, Bilbao and Sproul [155] also examined the night sky cooling potential of an uncovered water-based PV-PT-RC collector in Sydney, Australia. Experimental results indicated that around 750 Wh/m^2 of cooling flux (including radiative and convective contributions) could be collected per night during summer months. Further TRNSYS simulations showed that similar nightly cooling capacity can be realized other regions, with a minimum of 400 Wh/m^2 in Singapore to roughly 900 Wh/m^2 in Tucson, Arizona.

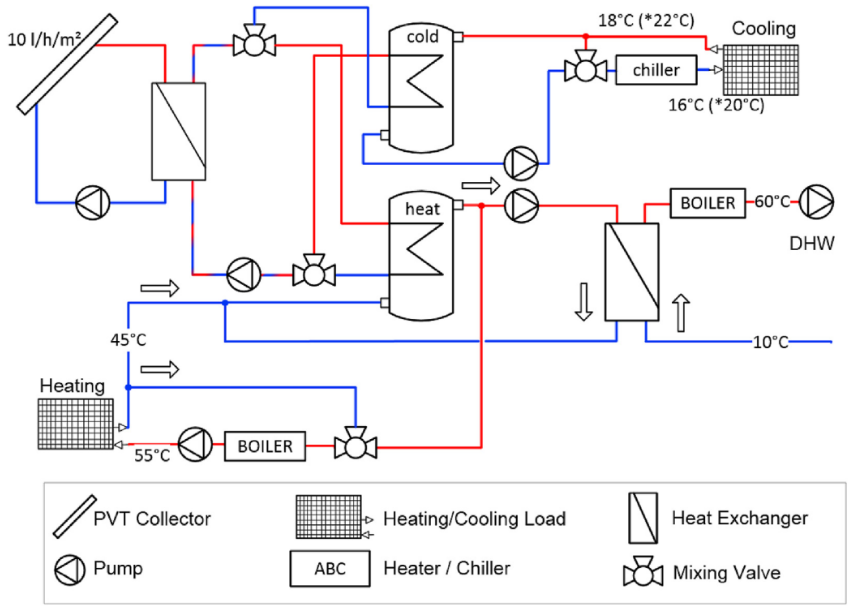

Fig. 23. Schematic diagram of a water-based and uncovered solar photovoltaic conversion, photothermal conversion, and radiative cooling (PV-PT-RC) system [158]. Reproduced with permission from Gürlich et al., *Energ. Buildings* 152, 701–717 (2017). Copyright 2017 Elsevier.

To achieve night sky cooling effect, the uncovered structure is widely adopted in PV-PT-RC modules given that the existence of glass cover will severely block long-wave emission from the PV layer to the sky. However, such a concession also leads to undesired negative consequences of intensifying convective heat loss during the daytime and convective cooling loss during the nighttime. Targeting greater overall energy outputs, a convective cover which can significantly suppress the convective thermal loss while showing high transmittance to sunlight and thermal radiation is essential. Polyethylene film is such a suitable substitute and is extensively used in radiative cooling devices.

Hu et al. [159] deployed a covered, practical-scale PV-PT-RC system and conducted outdoor experimental investigations in various operation modes in Hefei, China. Results indicated that the average electrical efficiency of the PV-PT-RC collector around noon was 10.3%, and the thermal efficiency at zero-reduced temperature was 55.3%. The net radiative cooling flux of the PV-PT-RC collector reached 72.0 and 30.8 W/m^2 respectively in a clear night and overcast night, respectively. To further figure out the output performance of the PV-PT-RC system in different working conditions, Hu et al. [162] developed a mathematic model on the PV-PT-RC system by MATLAB programming. The authors extensively studied the electrical, solar thermal, and radiative cooling performance of the system. Sensitive analysis was conducted to evaluate the effect of different structural parameters, i.e., insulation thicknesses, initial water temperature, packing factor, panel emissivity, and tank volume, on the key performance indicators of the system. Results indicated that, with a panel dimension of 1964 × 964 × 0.4 mm, the annual electrical, heat and cooling gains of the system reach 479.67, 2369.07 and 1432.49 MJ, respectively.

4.3 Heat pump-based systems

Except for employing air or water as the working fluid, some recent studies investigated the performance of the heat pump-based PV-PT-RC system using organic working mediums as the thermal carrier. The heat pump-based solar PV/T system is a well-recognized innovation and received extensive attention in the research community [26]. Compared to the common air source heat pump, this solar-assisted heat pump takes the absorbed solar thermal energy by the PV/T collector, thus making the evaporating temperature of the refrigerant at a high level and increasing the coefficient of performance (COP) of the heat pump. Moreover, comparing to the water- or air-based solar PV/T system, such a heat pump-based PV/T system employs refrigerant as the working medium that realizes phase change at a relatively low temperature in the PV/T collector (i.e., evaporator) and thus leading to less heat loss, higher electrical and thermal efficiencies [164]. Heat pump-based PV/T technology fits the energy demand profile in cold seasons but is of less value on hot days. Fortunately, most heat pumps are designed to operate reversibly, that is, the heat pump can work as a “cold pump” (i.e., refrigerator) by reversing the flow direction of refrigerant [165]. Considering that the uncovered PV/T collector shows nighttime radiative cooling potential, the cooling COP of the reversible heat pump will be enhanced by the PV/T collector in which the refrigerant condenses at a sub-ambient temperature. Therefore, the uncovered PV/T collector (i.e., PV-PT-RC collector) acts as the evaporator in the heating mode and as the condenser in the cooling mode for the heat pump system.

Chen et al. [166] introduced the concept of heat pump-based PV-PT-RC technology, and experimentally investigated the cooling performance of the hybrid system on summer nights. As results suggested, cooling COPs of water coolant producing on clear nights was 12.4% higher than those on cloudy nights, indicating that radiative cooling can benefit the cooling performance of the system. Zare et al. [167] put forward an indirect expansion/condensing heat pump-based PV-PT-RC system that mainly contains several uncovered PV/T collectors and a water-to-water heat pump. The uncovered PV/T collectors produce hot or cold water in different seasons, acting as the heat source or heat sink of the water-to-water heat pump. Simulation results indicated that the proposed system can save about 30% annual energy consumption compared to a referred air-source heat pump system. Zhou et al. [168] developed a roll-bond heat pump-based PV-PT-RC system with four uncovered PV/T collectors. The authors investigated its practical feasibility and trigeneration performance in Dalian, China. The average electrical efficiency and heating COP of the hybrid system were respectively 8.7% and 5.3 during the daytime. The cooling COP decreased gradually from 3.9 to 2.5 in the water-cooling phase and remained almost unchanged at 2.3 in the ice-making phase. Taking the uncovered PV/T collector as the heat source and heat sink of a reversible heat pump, Braun et al. [169] performed a parametric simulation study on the performance of the energy-saving system for two different buildings in three locations (Moscow, Stuttgart, and Dubai). The payback time for the passive house with a collector field area of 50 m^2 is respectively 12.8, 3.8, and 9.9 years for the three areas.

Based on the work conducted in Refs. [166] and [168], Liang et al. [170] further tested the refrigeration performance of the roll-bond heat pump-based PV-PT-RC system. The cooling COP decreased from 3.5 to 2.5 with an average value of 2.84 during the water-cooling stage and declined from 2.9 to 1.9 with an average value of 2.29 during the ice-making stage. Meanwhile, Lu et al. [171] conducted an experimental and simulation study on the cooling performance of a larger scale heat pump-based PV-PT-RC system involving twelve uncovered PV/T collectors, as shown in Fig. 24. The uncovered PV/T collectors served as the condenser to dissipate heat into the local environment by heat conduction and convection and into outer space by radiative cooling. The measured average cooling COP ranged from 1.8 to 2.1 during several summer nights in Dalian, China. Parametric simulation suggested that the overall radiative-convective heat dissipation density of the uncovered PV/T collectors declines by 7.4% as the ambient temperature increases from 20 to 35 °C. If the convective heat loss is suppressed, namely, as the wind velocity decreases from 1 to 0 m/s, the cooling flux of the uncovered PV/T collectors declines by 4.5%, resulting a cooling COP deduction of 20.0% for the system. Table A8 summarizes some applications of radiative cooling in solar photovoltaic/thermal systems.

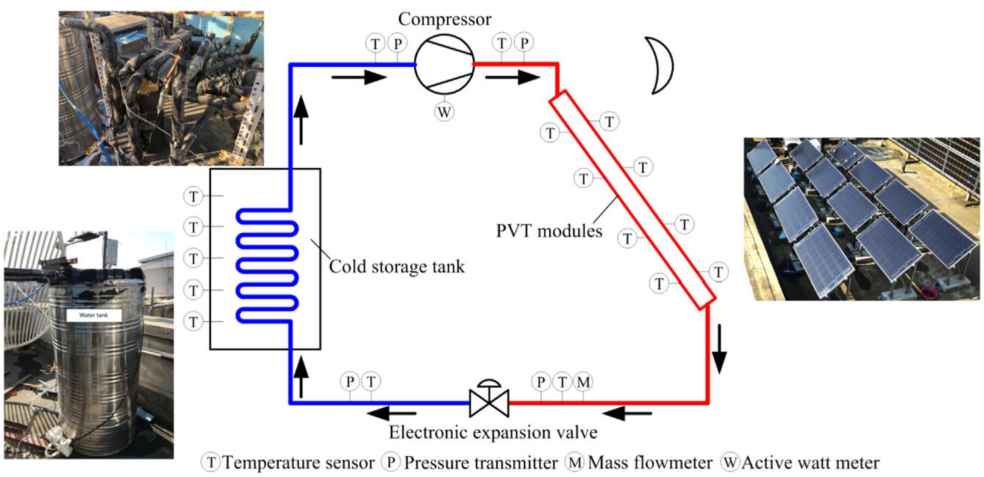

Fig. 24. Schematic and in-situ experimental setup of a larger scale heat pump-based PV-PT-RC system working in nighttime cooling mode [171]. Reproduced with permission from Lu et al., *Renew. Energ.* 146, 2524–2534 (2020). Copyright 2019 Elsevier.

5. Radiative cooling in solar thermal power systems

Radiative cooling also shows potential in improving the thermal-power efficiency of solar thermal power systems [49]. It is well-known that a Carnot heat engine working between a heat source and a cold reservoir has the upper limit of cycle efficiency [172]. Nevertheless, no matter for a Carnot engine or a real engine, efficiency benefit can be gained either from increasing the heat source temperature or lowering the heat sink temperature [173]. While benefits from increasing the heat source temperature are widely recognized by researchers, the potential of degrading the heat rejection temperature is usually not exploited. Radiative sky cooling offers an alternative solution to lower the condensation temperature of thermodynamic systems, including those solar thermal power systems. In general, the research of applying radiative cooling technologies in solar thermal power systems is still in its early stage. In what follows, related literatures are briefly summarized and divided into two categories, namely, (1) Solar thermal power plants, and (2) Other solar thermal power systems

5.1 Solar thermal power plants

Specific to the solar thermal power plants, especially the concentrated solar power plants (CSP), many have attempted to improve the maximum temperature [174]. Efforts have been devoted to designing better-performing SSACs at higher temperatures [175], conducting structural optimization of solar receivers [19], and developing working media such as molten salt [176] and supercritical carbon dioxide (S-CO_2) [177]. Although the privilege of enhancing the heat source temperature of CSP plants is extensively realized by the research community, depressing the condensing temperature is much less often pursued. Generally, to achieve higher efficiency, the vast majority of thermal power plants employ a wet cooling tower to cool down the water coolant, at where the coolant can potentially be cooled to the ambient wet-bulb temperature (WBT) [178]. It would be better if natural water bodies like lakes and rivers could serve as the heat sink, regardless of possible thermal pollution and ecological damage. Approximately 3.3 L water will be consumed for 1 kWh power generation in a wet-cooled parabolic trough CSP system [179]. However, CSP plants usually locate in desert areas (e.g., Northwestern China, the Middle East, the Mediterranean) where solar energy resources are abundant but water shortage is a huge challenge [180]. Therefore, finding an alternative solution to dump heat from the steam exhaust with the lowest possible water consumption is urgent for CSP plants. Dry cooling technology, based on a closed water loop, is introduced and developed under this background [181]. However, the water coolant in a dry-cooled (air-cooled) system can only be cooled down to the dry-bulb temperature at the most, which is somewhat higher than the WBT, depending on the local relative humidity [182]. Hence, dry-cooled CSP plants consume negligible water with a penalty of deteriorated thermal-power efficiency [183]. Fortunately, recent studies proved that radiative cooling could be a powerful backup for the dry-cooled CSP system in desert regions, where the arid climate favors high-performance radiative cooling [184]. The radiative cooler can be arranged as an additional cooling unit in the dry cooling system and can deliver up to 135 W/m^2 extra cooling flux under desired working conditions [184].

Smith PS and Smith OJ [185] were two pioneers who formally introduced radiative cooling technology into solar thermal power systems in their patent specification. The authors designed a radiative cooling unit as a heat sink for cooling down the water coolant of a Rankine cycle power system applied in the desert, in which a boiler and a series of flat-plate solar collectors serve as the heating unit. The radiative cooling panels, coated by titanium dioxide, can radiatively dissipate the condenser heat from the steam exhaust into the cold sky and reject most solar radiation. To maximize the solar reflection, the authors also suggested using reversible plastic mattresses floating on a cool water pond coated black on one side and silver on the other, with the black surface up at night as a radiative cooler and silver surface up during the daytime as a solar reflector. Similarly, in another patent, Mills et al. [186] proposed using different cooling approaches, including convective cooling and radiative cooling, to cool the coolant fluid of CSP plants.

It is important to note that, due to the distinct power density mismatch between radiative cooling and heat rejection load, large areas of radiative cooling field may be required to fully throw the condenser heat of a thermal power plant. Roughly estimation suggested that an area of 150 acres (about 0.6 km^2) of radiative coolers is needed for a 50 MW plant to dissipate approximately 150 MW heat per day [185]. Zeyghami and Khalili [184] gave a more detailed calculation of the required radiative cooling areas for a CSP plant in different cases. The highlight of their work is integrating daytime radiative cooling apparatuses into the dry-cooled CSP plant (see Fig. 25) to compensate for the power efficiency gap with wet-cooled plants. Two types of S-CO_2 cycles, namely simple S-CO_2 cycle and recompression S-CO_2 cycle, were designed and compared to assess the minimum radiative cooling fields of the plant. Results suggested that 4.38 and 10.46 m^2/kW radiative coolers are respectively required for the two S-CO_2 cycles running at a heat reservoir temperature of 800 °C, corresponding to performance improvement of 3.1% and 4.9%, respectively. To tackle the challenge that a huge land area is associated with the combination of radiative cooling in the CSP plant, Voorthuysen and Roes [187] presented a structural modification for integrating radiative cooling panels into the parabolic trough receivers. The authors arranged two radiative cooling panels, one is above and the other below the evacuated receiver, in the axisymmetric surface of the parabolic trough mirror. Benefited from this structure, the radiative cooling density can be enhanced as the incoming atmospheric radiation was restricted to low zenith angles. Meanwhile, as all of the direct solar radiation projected onto the mirror was reflectively collected by the receiver, simulated-based results indicated that the radiative cooler can reach sub-ambient temperatures even during the daytime. The water coolant dumps condenser heat to the radiative cooler via heat pipes before it flows back to the condensing unit of the CSP plant during the daytime or stores in a cold tank during the nighttime. The authors expected this structure optimization of the parabolic trough mirror can lead to a substantial cost reduction in land resources and initial investment, but no solid quantitative result was given.

In another study, by equipping the radiative cooling system with the same area of the solar mirror field, as well as arranging two cooling energy storages (a warm tank and a cold tank), Dyreson and Miller [188] carried out a numerical study on the feasibility of nighttime sky cooling technology for cooling a parabolic trough CSP plant with no or a little water consumption (see Fig. 26). Results revealed that, if the radiative cooling system is the same size as the solar collector field, 93% of the power plant's annual cooling load at the Daggett and 91% at Tucson can be covered by radiative cooling. The authors also noticed that the required large area of radiative cooling apparatuses is a fatal drawback of the new system and gave a compromised solution by placing the radiative cooling surface on the back of the parabolic trough mirror, thereby requiring no extra land size. The mirror is designed to rotate 180° from the diurnal solar collecting position for nighttime radiative cooling while maintaining the precise focus during the daytime. Similarly, Espargillier et al. [189] also suggested that the solar field can be arranged as the cooling unit in addition to being the solar concentrator. The authors demonstrated the feasibility of employing the large-scale mirror area as the substitute of the wet cooling tower and dry cooler of the CSP plant. The sky-facing side of the mirror area acts as the convective and radiative heat dissipater during the nighttime by sending the condensing heat to the local surroundings and outer space, while the ground-facing side is equipped with flat Roll-bond heat exchangers to distribute the heat transfer fluid. Results revealed that radiative cooling mechanism contributes to 95% and 53% of cooling demands for the linear Fresnel and parabolic trough CSP plants, respectively.

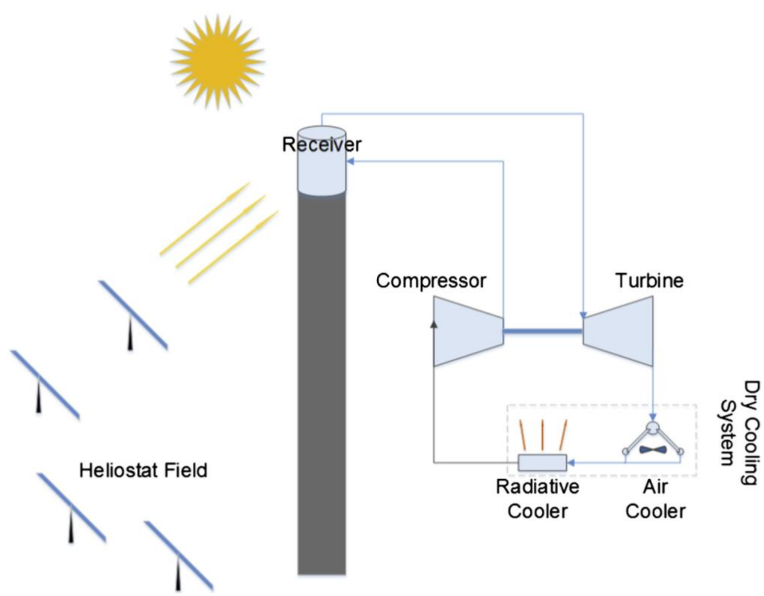

Fig. 25. Integration of daytime radiative cooling unit into a dry-cooled concentrated solar power tower plant [184]. Reproduced with permission from Zeyghami and Khalili, *Energ. Convers. Manage.* 106, 10–20 (2015). Copyright 2015 Elsevier.

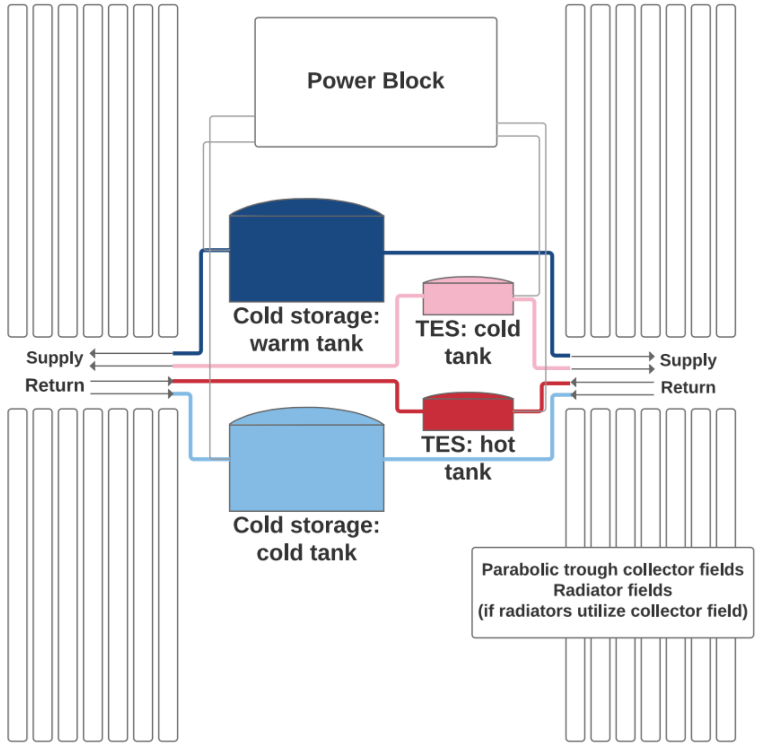

Fig. 26. Schematic of a typical solar parabolic trough power plant equipped with radiative cooling technology [188]. Reprinted with permission from Dyreson and Miller, *Appl. Energ.* 180, 276–286 (2016). Copyright 2016 Elsevier.

5.2 Other solar thermal power systems

Except for those studies specifically using radiative cooling to cool the large-scale concentrated solar power plant, a few works focused on boosting the power conversion efficiency of other solar energy-based thermal power systems by exploiting the coldness of the deep universe.

Zhao [190] and Westwood [191] collaboratively conducted theoretical and experimental studies on a novel thermal rectification system that mainly consisted of a black plate (acts as a diurnal solar absorber and nocturnal radiative cooler), a thermoelectric heat engine, two thermal diodes, and two thermal reservoirs (one is hot and the other is cold). Results indicated that up to 4 times of power output difference was observed between rectified (radiative cooling involved) and non-rectified systems. To amplify the temperature difference between the two temperature reservoirs of a heat engine, Chen et al. [141] introduced the idea of harvesting energy from the sun and outer space together. Simulated results indicated that the maximum efficiency of the heat engine reaches 88% when it simultaneously collects energy from the sun and outer space (see Fig. 27c). By contrast, the maximum efficiency decreases slightly to 85% by simply gathering heat from the sun (see Fig. 27a) and declines sharply to 25% by only gaining coldness from outer space (see Fig. 27b). In a following study, Li et al. [192] systematically elucidated the fundamental thermodynamic limits of four schemes (i.e., Shockley-Queisser limit, multicolor limit, blackbody limit, and Landsberg limit, see Fig. 28). If simultaneously collecting energy from the hot sun and cold universe, the maximum efficiencies of the single-junction solar cell (for Shockley-Queisser limit), multi-junction solar cell (for multicolor limit), and Carnot heat engine (for blackbody limit and Landsberg limit) are far higher than the existing established limits associated with exploiting only one thermodynamic resource (the sun or universe). In specific, with a fixed cell temperature of 300 K, the Shockley-Queisser limit, multicolor limit, blackbody limit, and Landsberg limit respectively reach 44.16%, 90.08%, 88.37%, and 102.89%.

Exploiting the distinct day-night ambient temperature difference in the arid desert caused by immense daytime solar energy absorbing and considerable nighttime radiative cooling, Cottrill et al. [193] designed a thermal resonator consisting of two thermal masses interfaced with a thermoelectric heat engine. The thermal resonator can convert the ambient temperature fluctuations into a spatial temperature difference for power generation. Thermal mass 1 shows high thermal effusivity and exists primarily at its phase transition temperature, while thermal mass 2 quickly responds and adopts the ambient temperature. After an approximately two-week period of experimental test in a harsh desert environment in Saudi Arabia, the apparatus showed the capacity of continually harvesting energy from the heating cycles during the daytime (~2 mW) and the cooling cycles during the nighttime (~100 μW), attributed to the different responsiveness of the two thermal masses to the ambient temperature. Similarly, under the driving force of achieving all-day electricity generation from environmental thermal energy, Yu et al. [194] presented a system including a solar absorber/radiative cooler (the top layer), a thermogalvanic cell (the middle layer), and a thermal storage unit (the bottom layer), as shown in Fig. 29. During the daytime, the top layer absorbs heat from the sun and local environment and elevates the temperature of the top electrode, while the bottom electrode remains relatively low temperature by storing latent heat into the PCM layer, forming a large temperature gradient across the thermogalvanic cell and thus yielding continuous electricity. During the nighttime, inversely, the top layer dissipates heat to outer space and local environment and cools the top electrode down, while the bottom electrode remains relatively high temperature by extracting heat from the PCM layer, creating an inverse temperature gradient across the thermogalvanic cell and inducing electricity as well. This tandem device realized continuous utilization of environmental thermal energy at both daytime (from the sun) and nighttime (from the cold sky), with the maximum electrical outputs being 0.6 W/m^2 and 53 mW/m^2, respectively. By radiative cooling and solar heating simultaneously, Ishii et al. [195] designed and prepared a thermoelectric device to increase the temperature gradient between the hot and cold sides and get enhanced thermoelectric voltage. The device consists of a solar transparent radiative cooler at the top, a spin Seebeck effect structure in the middle, and a solar absorber at the bottom. Experimental results (estimated from the figure the author provided) indicated that, with combined contribution from radiative cooling and solar heating, the device generated an inverse spin Hall effect voltage of 0.27 μV, which is higher than the radiative cooling-only (0.025 μV) and solar heating-only cases (0.23 μV). A summary of some applications of radiative cooling in solar thermal power systems is listed in Table A9.

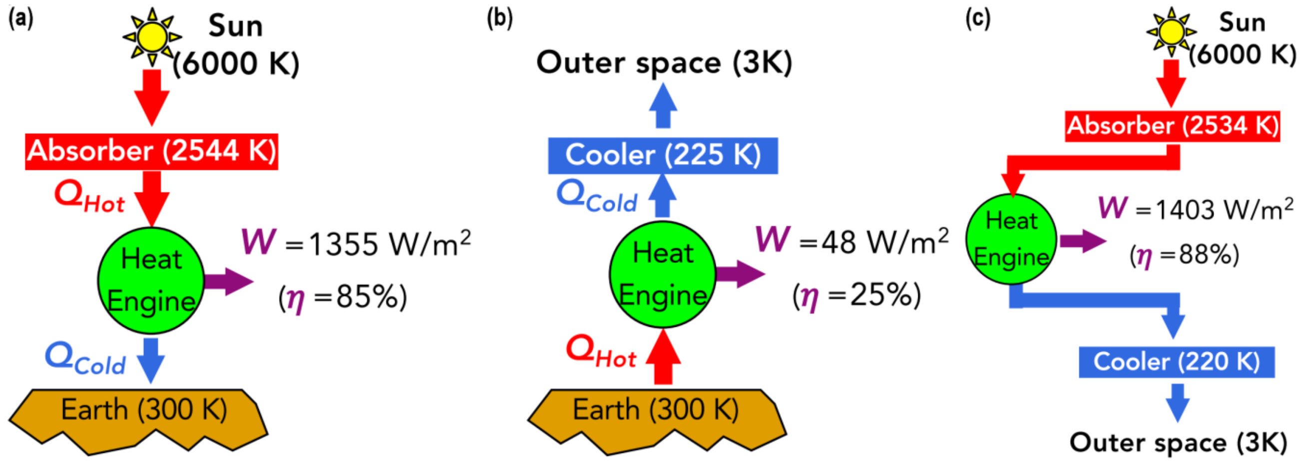

Fig. 27. Thermodynamic limits for a heat engine with different heat source and heat sink [141]. (a) Employing an absorber as the heat source and collecting heat from the sun. (b) Taking a cooler as the heat sink and dissipating heat to outer space. (c) Introducing an absorber as the heat source and a cooler as the heat sink to harvest energy from the sun and outer space simultaneously. (a)–(c) are reprinted with permission from Chen et al., *Joule* 3, 101–110 (2019). Copyright 2018 Elsevier.

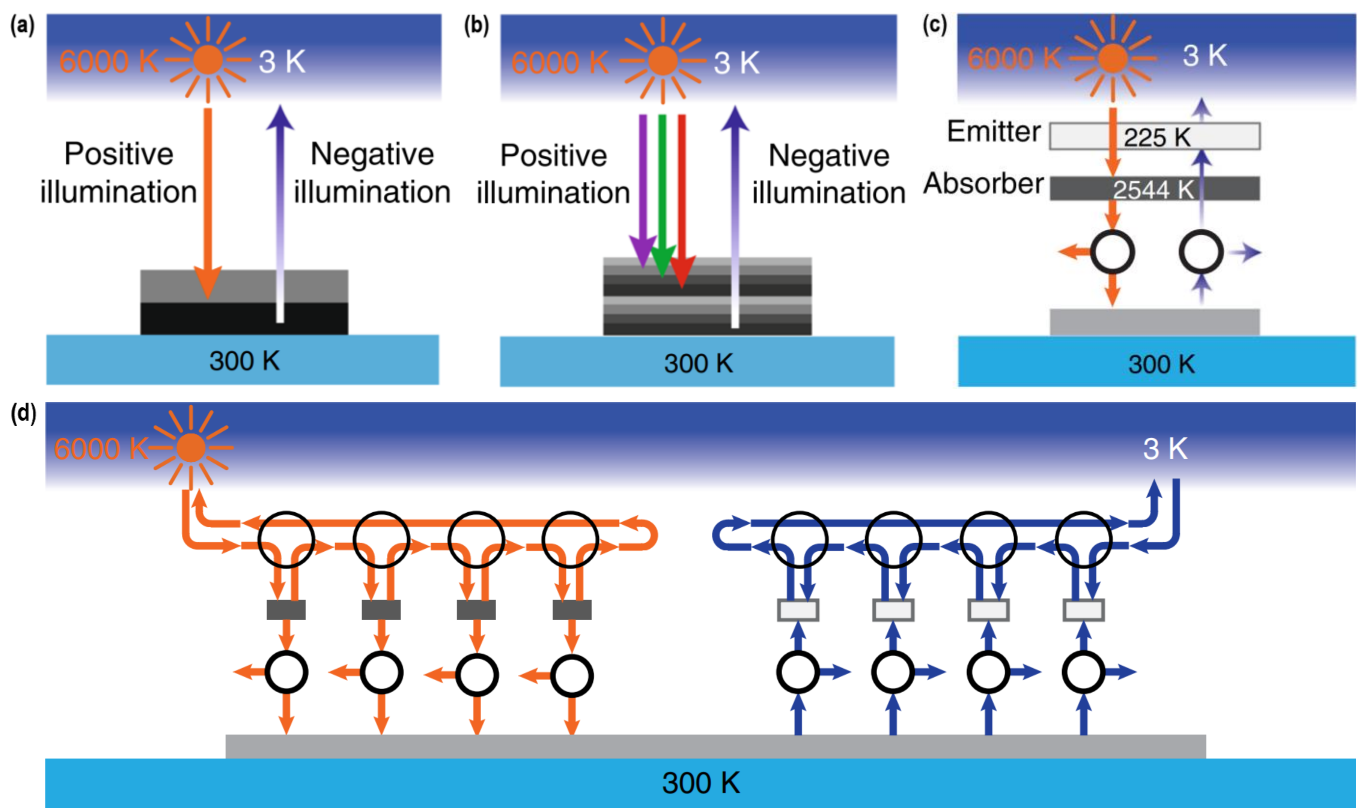

Fig. 28. Fundamental thermodynamic limits of four schemes simultaneously harvest energy from the hot sun and cold universe, with the operating temperature being 300K [192]. (a) Shockley-Queisser limit. (b) Multicolor limit. (c) Blackbody limit. (d) Landsberg limit. (a)–(d) are reprinted with permission from Li et al., *Light-Sci. Appl.* 9, 1–11 (2020). Copyright Li et al. 2020.

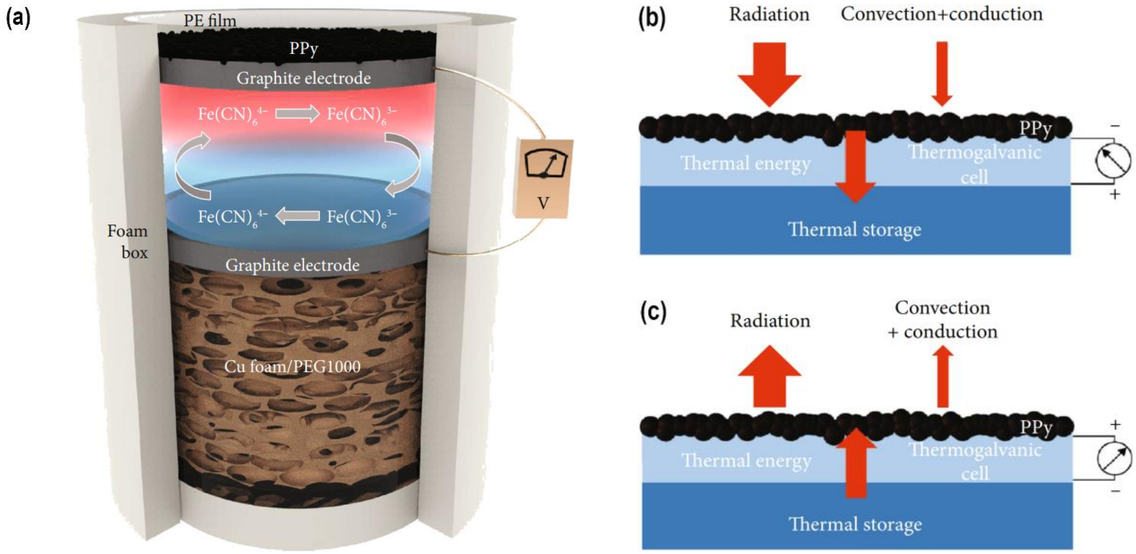

Fig. 29. A tandem device capable of all-day power generation via exploiting low-grade environmental thermal energy [194]. (a) Schematic of the tandem device. (b) Operation scheme during the daytime. (c) Operation scheme during the nighttime. (a)–(c) are reprinted with permission from Yu et al., *Research* 2019, 2460953 (2019). Copyright 2019 Boyang Yu et al.

6. Challenges and prospects

In summary, owing to the unique scheme of passively sending heat to outer space, radiative cooling has proved to be an exceptionally attractive strategy to be applied in solar energy systems, either increasing the power conversion efficiency of solar PV modules via lowering the cell temperature, or extending the effective operation period of solar PT and PV/T collectors to nighttime and cold months, or improving the thermal-to-power efficiency of solar thermal power plants through lowering the condensing temperature of the power block, etc. Recent advances have significantly promoted the development of radiative cooling in these mainstream solar energy systems, from conceptual designs to prototypes developing to real-world applications. However, the integration of radiative cooling and solar energy technologies is also encountering many barriers that need particular attention. On the other hand, these challenges also bring inspirations and opportunities to further combinate the two ultimate renewable energy from the universe delicately and advance the technology to wider applications. In this section, some misconceptions, challenges, and prospects are discussed.

(1) In passive PV cooling applications, the RC mechanism is usually applied together with above-bandgap effective absorption (EA) or sub-bandgap photons effective reflection (ER), but no study takes the strategy of RC+EA+ER simultaneously to minimize the cell temperature (based on the authors' literature searching). Besides, most of the existing studies involving radiative cooling of solar cells are simulation-based studies but lacks experimental demonstration. Future studies can make attempts in RC+EA+ER approach as well as prototype construction and experiments.

(2) Though lowering the operation temperature can increase the PV efficiency of a typical solar cell, one

cannot only take the cell-temperature reduction as the criterion to assess the contribution of a radiative cooling scheme in PV performance enhancement. Instead, the PV efficiency should be the final performance indicator to evaluate the usefulness of any PV cooling technology. For example, adding a radiative cooler atop the solar cell is a common approach to enhance long-wave thermal radiation, which may increase the optical loss of the solar cell and lower the PV efficiency due to the relatively low transmittance of the radiative cooler for above-bandgap photons. Therefore, only those pathways that can increase long-wave thermal radiation while enabling the solar cell to remain or even improve effective solar absorption can be recognized as useful radiative cooling strategies for PV cooling.

(3) Comparing the temperature reduction of a radiative cooling-based solar cell with the bare case (i.e., an unencapsulated solar cell with low long-wave emissivity) is unreasonable since most practical solar cells are covered by an encapsulation layer which has already shown relatively high long-wave emissivity. Therefore, it is more objective to evaluate the performance of the new radiative cooling enhanced solar cell by comparing it with the original encapsulated solar cell.

(4) Simply comparing the PV efficiency, thermal efficiency, and radiative cooling flux reported in different studies is unfair and insignificant since the material, environmental, and operating conditions are different. For instance, radiative cooling is preferable in arid and high-altitude areas, involuntarily resulting in a greater cell-temperature reduction for a PV cell or a higher net radiative cooling flux for a PT-RC collector in these regions. Besides, the performance evaluation criteria in different studies are different from each other. For example, some researchers claimed a high-level radiative cooling flux was observed, which was in fact the combined convective-radiative cooling flux. Therefore, it is of little reference value to compare the performance of different radiative cooling-based solar energy systems reported in different studies.

(5) The accessibility, scalability, and reliability of the radiative cooling involved material should be improved for further real-world applications. Existing radiative coolers in solar cells tend to be structurally complex and engineeringly elaborated. The polyethylene film widely used in radiative cooling-based solar energy installations is fragile and thus poses a challenge for long-term outdoor operation. Future researches should attach primary importance to alternative cover with better mechanical strength and weatherability.

(6) The side effect caused by the introduction of radiative cooling into common solar energy systems should be mitigated. The spectral conflict between radiative cooling and solar heating inevitably caused the deterioration of the solar thermal performance of the spectrally coupled PT-RC and PV-PT-PT collectors. The self-adaptive PT-RC or PV-PT-RC technologies seem to be favorable solutions for avoiding the spectral conflict and better accommodating the seasonal energy-consuming profiles of buildings. However, the spectral selectivity of existing self-adaptive coatings should be further optimized to achieve higher

heat-collection temperature and lower radiative cooling temperature. For the CSP plant, as a massive area of radiative cooling field is required to dissipate the condensing heat from the power block adequately, future studies should focus on how to decrease the land occupation prepared for radiative cooling. Potential solutions are integrating the radiative cooling unit into intrinsic components of the CSP plant such as the backside of the parabolic trough receivers, or taking the thousands of heliostats that show extremely high solar reflectivity and favorable long-wave emissivity as the radiative cooling field.

(7) In addition to the main application scenario of PT-RC and PV-PT-RC technologies, namely, the building sector, they also show great application potential in many other fields such as agriculture, industry, and vehicles. For instance, a large amount of heat is needed for crops in growing seasons, while in the harvest season heat is essential for crop drying and cooling energy is required for fresh crop storing. Therefore, a PT-RC or PV-PT-RC collector can benefit agricultural activities by providing heat and cooling energy in different processes.

(8) In addition to taking the natural water or air as thermal carriers, other working fluids such as nanofluids and heat-pipe based refrigerants can be adopted to increase the heat transfer coefficient or develop new structures for combined solar energy and radiative cooling systems.

(9) In addition to lowering the condensing temperature of CSP plants and solar heat pumps, the application of radiative cooling can be extended to other solar energy-driven thermodynamic cycles, such as solar absorption cooling systems, solar organic Rankine cycle systems, and solar thermoelectric cooling systems, etc.

(10) Considering that solar energy utilization and radiative cooling technologies share similarities in several aspects such as fundamental, renewability, and application scenarios, the well-developed and multitudinous solar energy technologies can be a perfect mirror and direct new advancements for the newly-developing radiative cooling art as well as those integrated solar energy and radiative cooling technologies (i.e., PV-RC, PT-RC, and PV-PT-RC). For example, solar tracking, concentrated structures, evacuated tubes, solar ventilation/chimney, solar-powered freshwater collection, etc., are good enlightenment for radiative cooling-related energy systems.

7. Conclusions

As a passive and sustainable cooling strategy dissipating heat to the cold universe, radiative sky cooling has received increasing attention and has experienced rapid advancements in recent years. In particular, various radiative cooling applications in solar energy systems display their unique attraction due to the characterization of simultaneously harvesting ultimate green energy from the sun and cold outer space. The performance or practicability improvement of a solar-driven system is contributed by further exploiting another renewable radiant energy from the extraterrestrial space. However, the integration of radiative cooling and solar energy technologies is still at the early-stage and is facing many challenges accompanied by opportunities. In general, with growing concerns of energy crisis and environmental pollution worldwide, the combination of radiative cooling and solar energy technologies is expected to take a more significant role in providing solutions for energy shortage, global warming, and air pollution, etc.

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Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Appendix

This appendix presented several Tables which summarize the application of radiative cooling in different solar energy systems.

Table A1. List of some PV cooling technologies involving radiative cooling enhancement solely.

Year	Reference	Location	Approach	Type of solar cell/module	Performance	Methodology
2004	Gilman and Ivanov [54]	-	Quantum-assisted emission	crystalline silicon PV cell/module	The PV module cools itself by 5 to 20 °C and earns 3 to 10% efficiency improvement.	Experiment and simulation
2014	Zhu et al. [55]	-	Micro-photonic design	Bare crystalline silicon wafer	The 2D square lattice of SiO_2 pyramid design realizes a 17.6 °C temperature reduction and a 7.9% relative efficiency increment compared to the bare silicon layer at 800 W/m^2 solar heating flux.	Simulation
2015	Wu et al. [56]	-	Coating the solar cell with a benzocyclobutene layer	GaAs nanowire solar cell	The solar cell gets a temperature decrement of almost 7 °C and an absolute efficiency increment of about 0.5% attributed to radiative cooling, compared to the planar structure.	Simulation
2015	Safi and Munday [64]	Earth surface and orbit	A hypothetic ideal radiative cooler	-	An efficiency improvement of 0.87% compared to a typical PV module in a terrestrial operation condition and an efficiency augment of up to 2.6% when applied in near-earth orbit.	Simulation
2016	Strojnik et al. [66]	-	Adding a low-iron soda-lime glass photonic crystal to the heat spreader	Thermophotovoltaic module	The operation temperature of the PV diode can be reduced by 91 °C, leading to a PV efficiency enhancement of 18% relatively.	Simulation
2017	Sun et al. [68]	-	Adding a multi-layer low-iron soda lime glass on the sky-facing side of the PV module	Concentrated PV module	The operation temperature of the PV module can be cooled by 14 °C more.	Simulation
2018	Zhao et al. [61]	Hefei, China	Adding a PDMS film atop the solar cell	Commercial silicon solar cell	The cell temperature was lowered by 1 °C in terrestrial conditions and can be reduced by 4.1 °C in extraterrestrial environments, corresponding to a relative efficiency increment of 0.45% and 1.85%, respectively.	Experiment and simulation
2019	Lee and Luo [62]	-	Designing a pyramid-structured PDMS layer as the cover of the solar cell	Organic, perovskite, and micro-crystalline silicon solar cells	The temperature of an organic, a perovskite, and a micro-crystalline silicon flexible solar cell can be lowered by 11 °C, 12 °C, and 16 °C, respectively.	Simulation
2019	Zhou et al. [69]	West Lafayette, USA	Adding a soda-lime glass-based radiative cooler atop the heat spreader	Concentrated PV module	A 10 °C temperature reduction attributed to radiative cooling was experimentally demonstrated, corresponding to a 5.7% increment in open-circuit voltage and a 40% extension in lifetime at 13 suns.	Experiment and simulation
2020	Wang et al. [70]		Attaching two soda-lime glass coolers on both sides of the heat sink	Concentrated PV module	A 5 to 36 °C temperature reduction and an 8% to 27% relative increase of open-circuit voltage for a GaSb solar cell were experimentally observed.	Experiment and simulation
2020	Banik et al. [65]	Earth orbit	Adding a layer of silicon-oxycarbonitride coating on the solar cell	CIGS solar cell	The cell temperature can be decreased up to 30 °C in orbit, corresponding to about 27% increment in maximum power output.	Experiment and simulation
2021	Wang et al. [63]	Chengdu, China	Adding a pyramid-textured PDMS film atop the solar cell	Commercial silicon solar cell	A 2 °C temperature reduction was experimentally demonstrated, corresponding to a relative efficiency improvement of about 1%.	Experiment and simulation

Table A2. List of some PV cooling technologies involving radiative cooling and above-bandgap absorption enhancements simultaneously.

Year	Reference	Location	Approach	Type of solar cell/module	Performance	Methodology
2015	Zhu et al. [74]	San Francisco, USA	Adding a visibly transparent photonic crystal thermal blackbody atop the solar absorber	Bare p-doped crystalline silicon wafer	The photonic crystal-based solar absorber could be cooled by 13 °C and 5.2 °C more than the bare absorber before and after a non-radiative cooling mechanism was introduced, respectively.	Experiment and simulation
2017	Lu et al. [60]	-	Adding an ultrabroadband textures imprinted glass atop the solar cell	Bare crystalline silicon PV module	The short-circuit current and the PV efficiency were increased by 5.12 and 3.13% in relative terms.	Experiment and simulation
2019	Lin et al. [77]	-	Adding an FPA-PDMS structure atop the encapsulant cover of the solar cell	Perovskite and commercial crystalline silicon solar cells	The PV efficiency improvement for the perovskite and crystalline silicon solar cells is 6.75% and 3.23%, respectively.	Experiment and simulation
2019	Long et al. [75]	-	Adding a thin SiO_2 micro-grating coating as the encapsulation cover of a doped silicon wafer	Bare doped silicon wafer	The SiO_2 micro-grating achieved an additional decrement in cell temperature by 2 °C compared to the bare doped silicon wafer.	Experiment and simulation
2019	Kumar and Chowdhury [78]	-	Adding a thin film of selected inorganic substance atop the solar cell	Bare crystalline silicon solar cell	The Si_3N_4-based solar cell can absorb 25 W/m^2 more solar irradiance and radiate 16.2 W/m^2 more heat in the "atmospheric window", corresponding to a PV efficiency increment of about 1% in absolute scale.	Simulation
2019	Kumar and Chowdhury [79]	-	Adding a selective radiative anti-reflective coating atop the solar cell	Commercial single-layered Si_3N_4 coated multi-crystalline silicon solar cell	The cell temperature can be lowered by 5.45 °C and the PV efficiency can be improved by 3.6% when the solar radiation, ambient temperature, and wind velocity are 1000 W/m^2, 30 °C, and 1m/s.	Simulation
2021	Perrakis et al. [80]	-	Adding a nano-micro-structured glass grating coating atop the solar cell	Bare doped silicon wafer and commercial crystalline silicon solar cell	• A relative solar absorption enhancement of about 25.4% and a cell temperature reduction up to 5.8 °C for the bare doped silicon wafer; • A relative PV efficiency increment of around 3.1% for the commercial crystalline silicon solar cell.	Simulation

Table A3. List of some PV cooling technologies involving radiative cooling and sub-bandgap reflection enhancements simultaneously.

Year	Reference	Location	Approach	Type of solar cell/module	Performance	Methodology
2017	Li et al. [84]	-	Adding a photonic cooler consisted of a multilayer dielectric stack atop the glass cover of the solar cell	Glass-covered crystalline silicon solar cell	The operation temperature of the solar cell can be reduced by 5.7 °C, corresponding to an absolute efficiency increment of 0.56%.	Simulation
2017	Sun et al. [83]	-	Adding a sub-bandgap optical filter atop and modifying the top and bottom surfaces of the solar cell	Silicon, CIGS, CdTe, and GaAs solar cells/modules	PV modules can be cooled up to 10 °C and a 0.5 percentage point efficiency increment can be achieved.	Simulation
2018	Zhao et al. [85]	-	Adding a photonic structure consisted of 1D multilayer stack and 2D photonic crystal atop the solar cell	Bare monocrystalline silicon solar cell	The diurnal electricity output and nocturnal radiative cooling flux increase by 6.9% and 30.5%, respectively, compared to a bare cell.	Simulation
2019	An et al. [73]	-	Adding a photonic radiative cooler that integrates a multilayer thin-film stack and a SiO_2 grating atop the solar cell	Bare thin-film crystalline silicon solar cell	The operation temperature of the solar cell can be decreased by over 10 °C, and the PV efficiency can be improved by 0.45%.	Simulation
2019	Li et al. [86]	-	Adding a hypothetical modified cover atop the solar cell	monocrystalline solar cell	The PV efficiency can be promoted by 4.55% when the ambient temperature and wind velocity are 36 °C and 2 m/s.	Simulation

Table A4. List of some detached solar photothermal conversion and radiative cooling systems.

Year	Reference	Location	Working medium	Application scenario	Performance	Methodology
1977	Givoni [96]	Haifa, Israel	Air	Buildings	The outdoor airflow under a white corrugated metal sheet could be cooled by about 4 to 5 °C below the ambient air temperature.	Experiment
1999	Saitoh [196]	Sendai, Japan	Water	Buildings	• The maximum average water temperature in the tank was 62 °C in heating mode; • The minimum water temperature in the tank reached 5.1 °C in cooling mode; • The fossil-fuel consumption and CO_2 emissions of the proposed house are 10% of those of the conventional energy-conservation house.	Experiment and simulation
2019	Parsons and Sharp [97]	Louisville, USA	R-124 and water	Buildings	The highest fraction of energy harvested from the sun and the cold sky reaches 0.707.	Simulation
2020	Li et al. [98]	Durham, USA	-	Buildings	• The maximum heat flux was 643.4 W/m^2 (with over 93% of solar thermal efficiency); • The maximum cooling power was 71.6 W/m^2.	Experiment and simulation
2021	Yoon et al. [99]	Three different cities	Water	Buildings	The proposed system can save annual power consumption by about 3% to 29% compared to the radiative cooling-assisted and solar-assisted heat pump systems.	Simulation

Table A5. List of some spectrally non-selective coupled solar photothermal conversion and radiative cooling systems.

Year	Reference	Location	Working medium	Application scenario	Performance	Methodology
1992, 1996	Erell and Etzion [100, 101]	Sde-Boqer, Israel	Water	Buildings	• An average radiative-convective cooling flux of 81 W/m^2 for three weeks; • A mean solar heating flux of 370 W/m^2 on a sunny winter day.	Experiment
2008	Wang et al. [113]	Tianjin, China	-	Buildings	• A maximum daily average solar thermal efficiency of 61%; • An average cooling capacity of 50 W/m^2.	Experiment
2012	Hosseinzadeh and Taherian [105]	Babol, Iran	Water	-	The overall radiative-convective cooling flux ranged from 23 to 52 W/m^2.	Experiment and simulation
2013	Ali [111]	Assiut, Egypt	Air and silica gel (desiccant)	Buildings	The outlet air temperature is lower than the ambient temperature by 5.5 to 7 °C, with the relative humidity below 40% at an air mass flow rate of 0.64 m^3/min.	Simulation
2015	Cui et al. [114]	Tianjin, China	Water (29% ethanol solution in winter)	Buildings	• The daily-average solar thermal efficiency was 39% and 27% for two panels with different coatings; • An average cooling flux of 30 W/m^2 in January.	Experiment
2017	Lee et al. [108]	Oita, Japan	Air and PCM	Buildings	• The maximum heat stored and released was about 6.6 kWh/day; • The total sensible heat reduction was around 28% compared with the conventional HVAC system.	Experiment and simulation
2018	Vall et al. [106]	Sixteen representative global cities	Water	-	At least 25% of cooling demand and 75% of domestic hot water demand can be covered by the system when applied to single-family, multi-family, and hotel buildings in San Francisco, Cape Town, Johannesburg, London, and Ottawa.	Simulation
2019	Hu et al. [115]	Hefei, China	Water	-	• The solar thermal efficiency at zero-reduced temperature was 63.0%; • The net radiative cooling flux was recorded at 55.1 W/m^2.	Experiment
2021	Bokor et al. [112]	Edirne, Turkey	Air	-	A 5 m^2 setup could cool the ambient air by up to 4 °C and realize an average cooling power density of 34.6 W/m^2.	Experiment

Table A6. List of some spectrally selective coupled solar photothermal conversion and radiative cooling systems.

Year	Reference	Location	Working medium	Application scenario	Performance	Methodology
1987	Matsuta et al. [118]	Aichi-ken, Japan	Water	-	• The maximum net solar heating flux was 610 W/m^2; • The maximum net radiative cooling flux was 51 W/m^2.	Experiment
2015	Hu et al. [119]	Hefei, China	-	-	The surface was 71 °C higher than the ambient temperature in solar heating mode and 13 °C lower in radiative cooling mode.	Experiment and simulation
2016	Hu et al. [120]	Hefei, China	Water	-	• The solar thermal efficiency at zero-reduced temperature was about 86.4% of that of the conventional solar collector; • The net radiative cooling flux was recorded at 50.3 W/m^2.	Experiment
2018	Hu et al. [121]	Hefei, China	Air	-	• The solar thermal efficiency at zero-reduced temperature reaches 45.9%; • The net radiative cooling flux reaches 36.6 W/m^2.	Simulation
2020	Zhao et al. [124]	-	-	-	• The surface can be heated to 79.1 °C above the ambient temperature during the daytime and cooled to 10 °C below at night.	Simulation
2020	Nwaji et al. [125]	Five Nigerian cities	Water	-	The water can be heated up to 45 °C above the ambient temperature during the solar heating mode and cooled down to at least 5 °C below the ambient temperature during the radiative cooling mode.	Simulation

Table A7. List of some other applications of radiative cooling in solar photothermal systems.

Year	Reference	Location	Combination form	Working medium	Application scenario	Performance	Methodology
2015	Sameti and Kasaeian [126]	Louisville, USA	Water wall-based structure	Water	Buildings	The hybrid system can cover 54% of annual heating demand and 53% of annual cooling demand.	Simulation
2018	Kort-Kamp et al. [137]	-	Optical switching	-	Human body	The "thermostat" can reach an equilibrium temperature of 6 °C below the midday ambient temperature in summer and 11 °C above in winter.	Simulation
2019	Yue et al. [130]	-	Double-side structure	-	Buildings, Human body	Compared to a bare house wall, the temperature of the Janus membrane was about 5.8 °C higher while around 9.6 °C lower after 180 min of solar radiation exposure for the Ag- and ZnO-based sides, respectively.	Experiment
2019	Peng et al. [138]	-	Optical switching	-	Human body	The VO_2/Ag-PET textile lowered the inner-room temperature by about 13.9 °C while remaining transparent to NIR radiation at low temperatures.	Experiment
2019	Mandal et al. [140]	New York, USA	Optical switching	-	Buildings	Switchable sub-ambient radiative cooling by about 3.2 °C in dry state and above-ambient solar heating by 21.4 °C in wet state.	Experiment
2019	Chen et al. [141]	San Francisco, USA	Spectrally filtered structure	-	-	The solar absorber and radiative cooler were respectively heated to 24 °C above the ambient temperature and cooled to 29 °C below the ambient temperature.	Experiment and simulation
2020	Vall et al. [127]	Lleida, Spain	Adaptive cover-based structure	Water	-	• The average solar thermal efficiency was 49%; • The average radiative cooling efficiency was 32%.	Experiment
2020	Hu et al. [129]	Hefei, China	Spectrally filtered structure	-	-	• The solar absorber could be heated to 139 °C above the ambient temperature; • The radiative cooler could be cooled to 11 °C below the ambient temperature.	Experiment and simulation
2020	Liu et al. [131]	Sanya and Tianjin, China	Double-side structure	Air	Buildings	The indoor air could be cooled to about 6.5 °C below the ambient temperature in Sanya in summer and reach 25 °C in Tianjin in winter daytime without additional heat supply.	Experiment and simulation
2020	Wang et al. [139]	-	Optical switching	-	Buildings, Automobiles	The compound meta-surface remained cool at 35 °C and stayed warm at 25 °C.	Simulation
2021	Song et al. [132]	Chengdu, China	Double-side structure	-	-	The Janus membrane could heat up an inner space by 12.5 °C in the heating mode and cool down the inner space by 10.9 °C in the cooling mode.	Experiment and simulation
2021	Hu et al. [133]	Hefei, China	Double-side structure	-	-	The bifacial module can realize a thermal efficiency of 83.3% in the solar heating mode and a net radiative cooling power of 69.9 W/m^2 in the radiative cooling mode under given conditions, provided the panel temperature equals the ambient temperature at 30 °C.	Simulation
2021	Zhou et al. [142]	Buffalo, USA	V-shaped structure	-	-	The radiative cooler realized a local cooling power density of 273.3 W/m^2 in a laboratory environment and a stagnation temperature of 14 °C below the ambient temperature in an outdoor condition.	Experiment and simulation

Table A8. List of some applications of radiative cooling in solar photovoltaic/thermal systems.

Year	Reference	Location	Working medium	Application scenario	Performance	Methodology
2001	Saitoh and Fujino [149]	Sendai, Japan	Water	Buildings	• The water in the water tank reached 65 °C in the heating season; • The water in the water tank decreased to 10 °C, and about 80% of space cooling energy can be covered by the radiative cooling system alone in the cooling season; • The proposed house consumes only 1/6 of fossil energy compared with the conventional house.	Experiment and simulation
2011	Eicker and Dalibard [150]	Madrid, Spain; Stuttgart, Germany	Water	Buildings	• Experimental radiative-convective cooling flux ranged from 60 to 65 W m^2 when the collector connected with a water tank and was around 40 to 45 W m^2 when the energy was directly used to cool a ceiling.	Experiment and simulation
2014	Lin et al. [145]	Wollongong, Australia	Air and PCM	Buildings	• The electrical and thermal efficiencies of the collector are 8.31% and 12.5%, respectively in winter daytime; • The average temperature decrement of the ambient air flowing through the collector is 2.4 °C in summer nighttime.	Simulation
2015	Massimo et al. [146]	Datong, China; Wollongong and Sydney, Australia	Air and PCM	Buildings	• The experimental electrical and thermal efficiencies of the collector were 8.2% and 9.0%, respectively in Datong in summer daytime; • The predicted cooling energy reaches 1.5 kW when the airflow rate is 300 L/s in Sydney in summer nighttime.	Experiment and simulation
2016	Bourdakis et al. [156]	Lyngby, Denmark	Water and PCM	Buildings	• The average electrical power ranged from 28.0 to 63.2 W/m^2; • The average water-heating flux ranged from 27 to 72.2 W/m^2; • The average water-cooling flux ranged from 56.3 to 82.1 W/m^2.	Experiment
2017	Hu et al. [143]	Hefei, China	-	-	• The PV-PT-RC panel could be heated to 67.3 °C above the ambient temperature during the daytime and cooled to 8.2 °C below at night.	Experiment and simulation
2017	Gürlich et al. [158]	Almada, Portugal; Bologna, Italy; Nottingham, UK	Water	Buildings	The trigeneration PV-PT-RC system can contribute up to: • 63% of the annual electricity consumption; • 47% of the domestic hot water demand; • 29 % of the cooling load if a cooling water temperature of 20 °C is set.	Experiment and simulation
2018	Hu et al. [159]	Hefei, China	Water	-	• The average electrical efficiency around noon was recorded at 10.3%; • The solar thermal efficiency at zero-reduced temperature was 55.3%; • The net radiative cooling flux reached 72.0 W/m^2.	Experiment
2018	Chen et al. [166]	Dalian, China	Refrigerant	-	• The average COP of water coolant producing and ice-making were 2.8 and 2.3, respectively.	Experiment
2018	Zare et al. [167]	Baltimore, USA	Water and refrigerant	Buildings	• The proposed system can save about 30% of annual energy consumption compared to a referred air-source heat pump system.	Simulation
2019	Zhou et al. [168]	Dalian, China	Refrigerant	-	• The average electrical efficiency of the hybrid system was recorded at 8.7%; • The average heating COP of the hybrid system was 5.3; • The cooling COP of the hybrid system reached up to 3.9.	Experiment and simulation

2020	Hu et al. [53]	-	-	-	The absorber plate can be cooled to nearly 11 °C lower than the ambient temperature and reach a maximum cooling flux of over 50 W/m^2.	Simulation
2020	Hu et al. [162]	Hefei, China	Water	-	Annual electrical, heat, and cooling gains of the PV-PT-RC system (collector area: 1.89 m^2) reach 479.67, 2369.07, and 1432.49 MJ, respectively	Simulation
2020	Braun et al. [169]	Moscow, Russia; Stuttgart, Germany; Dubai, UAE	Refrigerant	Buildings	The payback time for the passive house with a collector field area of 50 m^2 is 12.8, 3.8, and 9.9 years, respectively for Moscow, Stuttgart, and Dubai.	Simulation
2020	Liang et al. [170]	Dalian, China	Refrigerant	-	The average cooling COP was 2.84 during the water-cooling stage and 2.29 during the ice-making stage.	Experiment
2020	Lu et al. [171]	Dalian, China	Refrigerant	-	• The average cooling COP of the system ranged from 1.8 to 2.1 during several summer nights; • The overall heat dissipation density of the PV-PT-RC modules declines by 7.4% as the ambient temperature increases from 20 to 35 °C; • A cooling COP deduction of 20% occurs as the wind velocity decreases from 1 to 0 m/s.	Experiment and simulation
2021	Ahmed et al. [144]	Shanghai, China	-	-	• The PDMS coating helped lower the daytime operation temperature by 1.7 °C, corresponding to an increment in the electrical and exergy efficiencies by 0.76% and 0.5%, respectively; • An additional 4 to 7 W/m^2 nighttime cooling power could be gained due to the PDMS coating.	Experiment and simulation

Table A9. List of some applications of radiative cooling in solar thermal power systems.

Year	Reference	Location	Application scenario	Combination form	Performance	Methodology
2015	Zeyghami and Khalili [184]	Daggett, USA	Concentrated solar power plant	The radiative cooler acts as an auxiliary condenser	• A 4.38 m^2/kW radiative cooling field improves the cycle performance of a simple supercritical carbon dioxide cycle-based power plant running at 800 °C heat reservoir temperature by 3.1%. • A 10.46 m^2/kW radiative cooling field improves the cycle performance of a recompression supercritical carbon dioxide cycle-based power plant running at 800 °C heat reservoir temperature by 4.9%.	Simulation
2015	Zhao [190] and Westwood [191]	-	Thermal rectification system	A black plate acts as a diurnal solar absorber and nocturnal radiative cooler	Up to 4 times of power output difference was observed between rectified (radiative cooling involved) and non-rectified systems	Experiment and simulation
2016	Dyreson and Miller [188]	Daggett and Tucson, USA	Concentrated solar power plant	The radiative cooler cools the cold storage at night	93% of the power plant's annual cooling load at the Daggett and 91% at Tucson can be covered by the radiative cooling system which equals the solar collector field in area.	Simulation
2017	Espargillier et al. [189]	-	Concentrated solar power plant	The solar mirror acts as the radiative cooler at night	Radiative cooling contributes to 95% and 53% of cooling demands for the linear Fresnel and parabolic trough concentrated solar power plants, respectively.	Simulation
2019	Chen et al. [141]	-	Carnot heat engine	The radiative cooler acts as the heat sink of the engine	The maximum efficiency of the heat engine reaches 88% when it simultaneously collects energy from the sun and outer space	Simulation
2020	Li et al. [192]	-	Single-junction solar cell, multi-junction solar cell, and Carnot heat engine	The universe acts as the heat sink of the solar cell; The radiative cooler acts as the heat sink of the engine	With a fixed cell temperature of 300 K, the Shockley-Queisser limit, multicolor limit, blackbody limit, and Landsberg limit respectively reach 44.16%, 90.08%, 88.37%, and 102.89% when simultaneously harvesting energy from the sun and outer space.	Simulation
2019	Cottrill et al. [193]	Thuwal, Saudi Arabia; Cambridge, USA	Thermal resonator	Radiative cooling creates a low ambient temperature at night	The thermal resonator showed the capacity of continually harvesting energy during the daytime (~2 mW) and night-time (~100 μW)	Experiment and simulation
2019	Yu et al. [194]	Wuhan, China	Thermogalvanic cell	The top layer acts as a solar absorber during the daytime and a radiative cooler at night	The device realized a maximum electrical output of 0.6 W/m^2 during the daytime and 53 mW/m^2 during the nighttime.	Experiment
2021	Ishii et al. [195]	Tsukuba, Japan	Thermoelectric device	A solar transparent radiative cooler acts as the cold side	The device generated an inverse spin Hall effect voltage of 0.27 μV, which is higher than the radiative cooling-only (0.025 μV) and solar heating-only cases (0.23 μV).	Experiment and simulation

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Highlights

1. Principles of radiative cooling and four solar energy technologies are introduced.

2. Applications of radiative cooling in these solar energy systems are reviewed.

3. Some current challenges and potential applications are presented and discussed.

Declaration of interests

☑The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: