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Photonics and thermodynamics concepts in radiative cooling

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Radiative cooling is a ubiquitous passive process that uses photon heat flow to carry away energy and entropy. Radiative cooling processes have been studied in the scientific literature for many decades, but advances in nanophotonics have enabled recent breakthroughs in daytime radiative cooling, which have inspired intense research efforts in this area. Radiative cooling is now emerging as a frontier in renewable energy research, with important potential for wide ranges of applications. In this Review, we discuss the fundamental photonics and thermodynamics concepts that underlie the processes of radiative cooling. Understanding of these concepts is essential both for the demonstration of cooling effects and for the development of practical technology.

Thermal radiation, or photon heat flow, carries both energy and entropy[1]. When a hot and a cold object undergo radiative exchange, there is a net photon heat flow from the hot to the cold object[2,3]. Such a photon flow carries both energy and entropy away from the hot object, leading to radiative cooling of that hot object. The radiative cooling processes are passive processes that do not require any energy input. However, to perform radiative cooling on a hot object, one does need to couple it radiatively to a cold object that serves as the heat sink.

Radiative cooling processes are in fact quite common in everyday life. As one example, the ambient environment is usually colder than the human body. Hence, the human body can radiatively cool: it can dissipate a significant portion of its heat via thermal radiation to the ambient environment. As another example, outer space, at a temperature of 3 K, is far colder than the ambient environment on Earth. Moreover, the Earth's atmosphere is largely transparent in the mid-infrared wavelength range of 8–13 µm. This wavelength range, commonly referred to as the transparency window of the atmosphere, coincides with the spectral peak of the thermal radiation from an object maintained around the ambient temperature. Consequently, a sky-facing object on Earth's surface can radiate its heat through the atmosphere to the cold outer space. This process has been used for many decades in the demonstration of night-time radiative cooling[4–11], where a black emitter facing the night sky can become colder than the ambient temperature.

While radiative cooling processes do naturally occur, for practical applications, it is almost always necessary to engineer and control such radiative cooling processes. Certainly, to enhance radiative cooling it is useful to create structures with high emissivity in the mid-infrared wavelength range. Moreover, since the cooling demand typically peaks during the day, it is important to be able to perform daytime radiative cooling under direct sunlight. For the purpose of daytime radiative cooling, it is no longer possible to use the black emitters that are commonly used in night-time experiments, since a black emitter will be heated by the sunlight. Therefore, control of the absorptivity and emissivity over a broad wavelength range that spans from the ultraviolet to the mid-infrared becomes essential. Recent breakthroughs in radiative cooling have been built directly on the developments of nanophotonic structures, where designing subwavelength structural features has resulted in unprecedented capabilities to control light over very broad wavelength ranges.

The process of radiative cooling directly uses the photon heat flow to carry away energy from the hot object. Such heat flow can be harvested to generate useful work. In the understanding of such an energy-harvesting process, thermodynamics considerations, including both energy and entropy aspects, play a critical role. In particular, understanding the entropy content of thermal radiation is essential in determining the ultimate limit of energy harvesting in radiative cooling.

In this Review, we discuss the fundamental photonics and thermodynamics concepts that underlie the processes of radiative cooling. Understanding these concepts is essential both for the demonstration of cooling effects and for the development of practical technology. Radiative cooling is now emerging as a frontier in renewable energy research, with important potential for wide ranges of applications.

Photonics concepts

The demonstration of radiative cooling concepts relies on the capabilities of photonic structures to control light over a broad spectral range. In the past two decades, significant progress has been made in tailoring the thermal emissivity of photonic structures[12–19]. Moreover, in general, the strength of the interaction between light and a structure depends critically on the relevant length scales of the structure. For example, a dielectric particle can resonantly scatter light when its size is comparable to the wavelength[20]. Similarly, a photonic bandgap effect occurs when the periodicity of the structure approximately matches the wavelength. Exploiting this property, one can construct spectrally selective structures that strongly interact with one part of the spectrum while having a relatively weak interaction with the other parts.

Daytime radiative cooling. To illustrate the photonics concepts involved in radiative cooling, we first consider the example of daytime radiative coolers (Fig. 1a) as proposed in ref. [21] and demonstrated initially in ref. [22]. Such a radiative cooler, given access to a clear sky,

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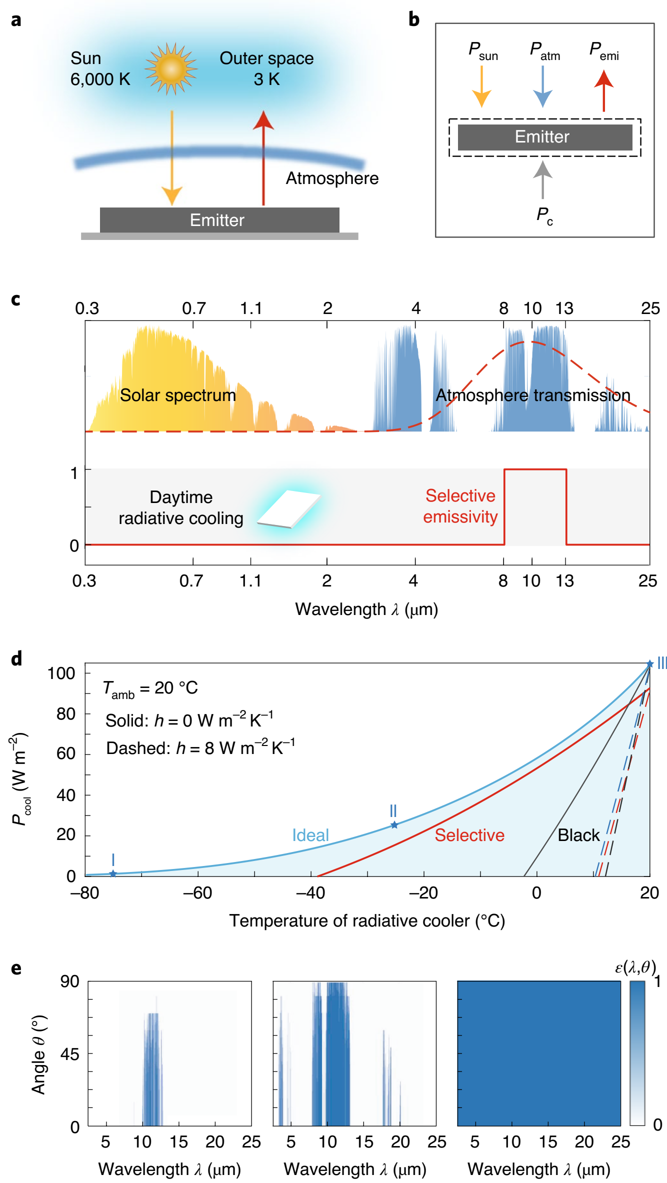

Fig. 1 | Daytime radiative cooling. **a**, Radiative heat-exchange process of daytime radiative cooling. **b**, Thermal balance of daytime radiative cooling. **c**, Solar spectrum (yellow shaded area) and the atmosphere transmission spectrum in the mid-infrared wavelength range (blue shaded area). The transparency window of the atmosphere at 8–13 μm has a large spectral overlap with the blackbody radiation spectrum at typical ambient temperatures near 300 K (red dashed curve). A spectral selective emitter (red solid curve) with an emissivity of unity at 8–13 μm and zero emissivity at other wavelengths can be used to realize daytime radiative cooling. **d**, Net cooling power P_{cool} as a function of radiative cooler temperature T under various emissivity profiles $\varepsilon(\lambda, \theta)$, including the 8–13 μm spectral selective emitter (red), black infrared emitter (black) and optimal spectral-angular-selective emitter (blue). The light-blue shaded region defines the region where radiative cooling can operate. **e**, The optimal emissivity profiles of the radiative cooler targeting different operating objectives (blue stars on the blue curve in **d**): to achieve a low equilibrium temperature (left); to maintain the radiative cooler at a certain temperature that is below the ambient temperature while maximizing the net cooling power (middle); and to maintain the radiative cooler at or above the ambient temperature while maximizing the net cooling power (right).

can reach a sub-ambient temperature, even under direct sunlight. Here we assume that such a radiative cooler has an area A and a temperature T, and faces the sky with its the normal direction pointing to the zenith direction. Its thermal balance is shown in Fig. 1b. Its cooling power P_{cool} can then be described as:

$$P_{cool}(T) = P_{rad}(T) - P_c. \tag{1}$$

Here, $-P_{rad}$ is the radiative thermal load of the emitter due to the radiative exchange with the surrounding environment. In the context of daytime radiative cooling, $P_{rad} = P_{emi}(T) - P_{atm}(T_{amb}) - P_{sun}(T)$, where

$$P_{emi}(T) = A\int d\Omega \cos\theta \int_0^{\infty} d\lambda I_{BB}(T,\lambda)\,\varepsilon(\lambda,\theta) \tag{2}$$

is the power emitted from the cooler. Here, Ω is a solid angle, θ denotes the angle between the direction of the solid angle and the normal direction of the surface, $\varepsilon(\lambda, \theta)$ is the emissivity of the object at a wavelength λ and angle θ, and $I_{BB}(T, \lambda)$ is the spectral irradiance of a blackbody.

$$P_{atm}(T_{amb}) = A\int d\Omega \cos\theta \int_0^{\infty} d\lambda I_{BB}(T_{amb},\lambda)\,\varepsilon_{atm}(\lambda,\theta)\varepsilon(\lambda,\theta) \tag{3}$$

describes the portion of the downwards radiation from the atmosphere that is absorbed by the radiative cooler. Here, the emissivity of the atmosphere is $\varepsilon_{atm}(\lambda, \theta) = 1 - t(\lambda)^{1/\cos\theta}$, with $t(\lambda)$ being the transmission coefficient of the atmosphere in the zenith direction.

$$P_{sun}(T) = A\cos\theta_{sun} \int_0^{\infty} d\lambda I_{sun}(\lambda)\,\varepsilon(\lambda,\theta_{sun}) \tag{4}$$

is the incident solar power absorbed by the radiative cooler, where $I_{sun}(\lambda)$ is the solar spectrum and θ_{sun} denotes the direction of the incoming sunlight. In equation (1),

$$P_c = Ah(T_{amb} - T) \tag{5}$$

is the heat load on the cooler due to the conductive and convective heat exchange with the environment, including external objects that the cooler is in contact with as well as adjacent air, and h is a combined non-radiative heat transfer coefficient that describes such conductive and convective heat exchange.

The equations above highlight the central role that the emissivity $\varepsilon(\lambda, \theta)$ plays in controlling the behaviour of the radiative cooler. To achieve daytime radiative cooling, the emissivity must be designed to exploit various aspects of the radiative environment surrounding the cooler (Fig. 1c): (1) The atmosphere possesses a transparency window in the mid-infrared wavelength range of 8–13 μm. This window has a very large overlap with the blackbody radiation spectrum at typical ambient temperatures near 300 K. The cooler therefore should have high emissivity within such a transparency window so that it can dissipate heat to outer space through its thermal radiation P_{emi}. (2) In the mid-infrared wavelength range, outside the transparency windows, there is significant downwards radiation from the atmosphere P_{atm}. The cooler needs to have a low emissivity outside these windows to minimize the absorption of such downwards radiation. (3) In the daytime, there is also significant incoming power from the sunlight. Thus, the cooler needs to have minimum emissivity in the solar wavelength range to minimize the parasitic heat absorption from the sun, P_{sun}.

To further illustrate the importance of emissivity on the cooling performance, in Fig. 1d, based on equation (1), we plot the cooling power P_{cool} as a function of the temperature of the radiative cooler T, for various emissivity profiles $\varepsilon(\lambda, \theta)$. The equilibrium temperature T_{eq}, where $P_{cool}(T_{eq}) = 0$, defines the lowest temperature that the emitter can reach. Here we assume that $T_{amb} = 20\,°C$ and a transmission spectrum of the atmosphere as shown by the light-blue region in Fig. 1c. Such a transmission spectrum corresponds to the atmosphere with an ambient temperature T_{amb} of 20 °C and 20% relative humidity[23]. We also assume that the emitters have zero absorption in the solar wavelength range ($P_{sun} = 0$). We first consider the case of perfect thermal insulation ($h = 0$). A spectral selective emitter (the solid red curve in Fig. 1c), which has an emissivity of unity in the 8–13 μm wavelength range and zero emissivity elsewhere, can reach $T_{eq} - T_{amb} \approx -60\,°C$ (the solid red curve in Fig. 1d). Experimentally, radiative cooling to a temperature of 40 °C below ambient has been demonstrated in ref. [24] using a selective emitter and a vacuum chamber for thermal insulation. By contrast, a blackbody emitter, which has an emissivity of unity over the entire mid-infrared wavelength range, can only reach a much higher temperature of $T_{eq} - T_{amb} \approx -20\,°C$ (the solid black curve in Fig. 1d). Moreover, for a given atmosphere transmission spectrum, to reach the lowest temperature possible, theoretically one can optimize $\varepsilon(\lambda, \theta)$ for every angle and wavelength[25,26] (Fig. 1e, left). Such an optimized emitter can reach $T_{eq} - T_{amb} \leq -100\,°C$ (the solid blue curve in Fig. 1d) with perfect thermal insulation ($h = 0$). Compared with the case of perfect thermal insulation as discussed above, in typical outdoor conditions without sophisticated thermal insulation (assuming $h = 8\,W\,m^{-2}\,K^{-1}$), the magnitude of the temperature reduction is far lower (Fig. 1d, dashed lines).

The emissivity profile optimized for the objective of achieving the lowest possible temperature features a narrow-band angle-selective profile (Fig. 1e, left). This is a consequence of optimizing the radiative cooling process in every angle and wavelength channel by tuning the emissivity, in consideration of the wavelength and angular dependency of the atmospheric radiation. Along this direction, an angle-selective emitter for a radiative cooler has been demonstrated experimentally in ref. [27]. An emissivity optimized for other objectives has a different profile. For example, to maintain the radiative cooler at or above ambient temperature, while maximizing the net cooling power, a black emitter in the infrared wavelength range with a broad angular range should be used (Fig. 1e, right). As another scenario, one may wish to maintain the radiative cooler at a certain temperature that is below the ambient temperature while maximizing the net cooling power. For this case, the spectral bandwidth of the optimal emissivity becomes broader (Fig. 1e, middle) compared with the profile required for achieving a very low temperature. A number of emerging applications for daytime radiative cooling, including non-evaporative water cooling for air-conditioning systems[28,29], energy harvesting[30] and water harvesting[26,31,32], correspond to this scenario. Therefore, depending on the desired working conditions, the optimized emissivity profile needs to be carefully tuned. In general, optimization of the emissivity profile $\varepsilon(\lambda, \theta)$ reflects the following trade-off between the equilibrium temperature and the cooling power: to reach a low equilibrium temperature requires a narrow-band angle-selective emitter, whereas to have a high cooling power requires a broad-band emitter with a large angular range.

As discussed above, achieving sub-ambient daytime radiative cooling requires detailed control of the emissivity and absorptivity profile of the cooler. Recent advances in nanophotonics have provided powerful tools to satisfy these requirements. Figure 2a shows the theoretical design of a photonic structure capable of achieving daytime radiative cooling[21]. Figure 2b shows the structure and results from the experimental demonstration in 2014[22], where the experimental structure consists of several alternating layers of SiO_2 and HfO_2 deposited on a silver (Ag) mirror. SiO_2 is known to produce strong thermal emission in the mid-infrared wavelength range due to its phonon polaritons. The combination of SiO_2 and HfO_2 layers further tailors the emissivity spectrum in the mid-infrared, as well as the reflectivity spectrum of the silver mirror in the ultraviolet wavelength range that is within the solar spectrum. When placed in a rooftop measurement setup (Fig. 2c), such a structure was able to reach a temperature that is 5 °C below the ambient temperature—in spite of having about 900 W m^{-2} of sunlight directly impinging on it.

Since the initial demonstration, daytime radiative cooling has now been realized in a very large number of different structures in a diverse set of material systems[27,28,33–49], including polymer films[27,28,35] (Fig. 2d), glass–polymer metamaterials[36] (Fig. 2e), hierarchically porous polymers[37,50], structural woods[38] (Fig. 2f) and polymer nanofibre films[39]. Moreover, significant efforts have been made towards the scalable manufacturing of daytime radiative coolers and towards the large-scale deployment of this technology for many different applications. For example, as an important step towards integrating radiative cooling technology into air-conditioning systems, sub-ambient non-evaporative fluid cooling has been demonstrated using large-area (~1 m^2) fluid-cooling panels (Fig. 2d). These panels can cool water to 3–5 °C below the air temperature[28]. Injecting such cooled water into the air-conditioning systems should improve the system efficiency by 20% (refs. [28,51]). Radiative cooling also enables water harvesting from the ambient atmosphere. By cooling to a temperature below the dew point, water can be harvested on a radiative cooler during both the day and at night-time[32,52].

Most existing radiative cooling systems are static, that is, the thermal emissivity profiles of the photonic structures are fixed once constructed. However, the ambient temperature varies across the days and seasons. When the ambient temperature is below a critical temperature and hence cooling is no longer desired, radiative cooling may no longer be desirable and may even increase the energy consumption if heating is required. Therefore, it would be desirable to achieve an active radiative cooling system, where cooling can be adjusted or turned on/off. Efforts towards an active radiative cooling system have been made[53] using phase-change materials[54], liquid–porous polymer mixtures[55], mechanical deformation[56], translation and rotation[57].

In most radiative cooling systems, the solar radiation is reflected and therefore not harvested. On the other hand, it is in fact possible to perform simultaneous solar-energy harvesting and radiative cooling. Reference [58] placed a solar absorber consisting of a germanium wafer on top of a radiative cooler. The germanium wafer is transparent in the mid-infrared wavelength range. Therefore, it can harvest the incoming sunlight, while allowing the thermal radiation from the cooler to transmit into the sky. In the experiment, the germanium wafer is heated above the ambient air temperature by the sunlight, whereas the radiative cooler remains at a temperature that is below ambient. From a practical point of view, the results here indicate that radiative cooling need not compete with solar cells for roof space. The same roof space can be used to accommodate both renewable energy technologies.

Solar cell cooling. The success in the demonstration of daytime radiative cooling has also motivated researchers to examine many other situations where similar concepts can be fruitful. One example is to perform radiative cooling of solar cells[59–65]. During operations, standard solar cells heat up under sunlight, and the resulting increased temperature has adverse consequences on both the solar cell efficiency and reliability[66]. On the other hand, a solar cell naturally faces the sky and therefore can radiate some of its heat out as infrared radiation. Therefore, it is important to explore the photonic approach to engineer the radiative heat transfer process of solar cells.

To develop a photonic approach for solar cell cooling, one needs to consider the impact of different parts of solar and thermal spectra on the radiative thermal load of a solar cell[61] (Fig. 3a). The radiative thermal load of a solar cell can be computed using formalisms that are similar to equations (1)–(5). Certainly, solar cells are designed to absorb sunlight. In particular, the part of the solar spectrum that is

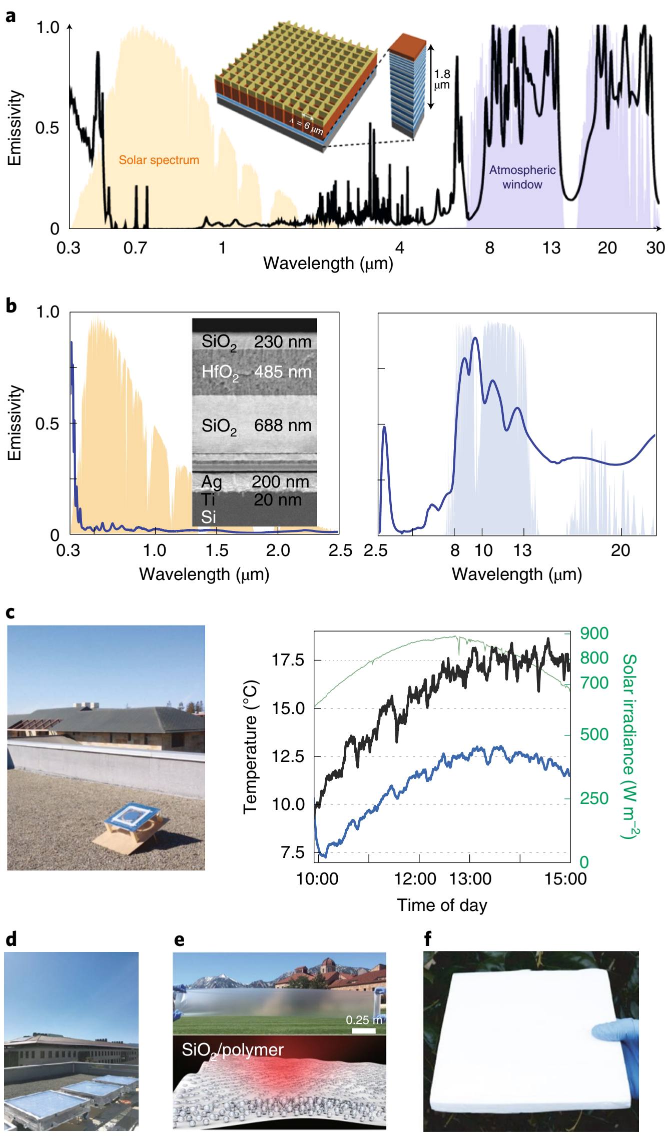

Fig. 2 | Recent advances in daytime radiative cooling. a, Theoretical nanophotonic design of a daytime radiative cooler. **b**, Emissivity profile of an experimental daytime radiative cooler in the solar (left) and infrared (right) wavelength range. The inset shows the structure. **c**, Experimental demonstration of daytime radiative cooling. When placed on the rooftop (left), the cooler reaches a temperature of 5 °C below the ambient air under direct peak sunlight (right). **d**, Fluid-cooling panel system for sub-ambient non-evaporative fluid cooling. **e**, Photo (top) and schematic (bottom) of large-scale photonic radiative cooler containing randomly distributed SiO_2 microspheres in polymer. **f**, A radiative cooling structural material made of wood. Panels adapted with permission from: **a**, ref. [21], American Chemical Society; **b**,**c**, ref. [22], Springer Nature Ltd; **d**, ref. [28], Springer Nature Ltd; **e**, ref. [36], AAAS; **f**, ref. [38], AAAS.

above the bandgap of the solar cell contributes to the generated photocurrent. Therefore, the photonic approach for solar cell cooling should not affect the absorption of this usable part of the solar spectrum. On the other hand, part of the solar spectrum that is below the bandgap of the solar cell does not contribute to the photocurrent. To minimize the radiative heat load of the solar cell it is important to minimize the absorption of the sub-bandgap solar spectrum. Finally, in the mid-infrared wavelength range of 4–30 μm, there is minimal solar power. On the contrary, the infrared radiation from the cell in this wavelength range can carry the heat away. Therefore, it is also beneficial to maximize the thermal emissivity of the cell in this mid-infrared wavelength range. We note that a solar cell typically operates above ambient air temperature. Thus this entire mid-infrared wavelength range of 4–30 μm can be used for radiative cooling purposes[59]. There is no need to restrict the emission of the cell structure to only the transparency window of the atmosphere as in the case of daytime radiative cooling.

One approach towards solar cell cooling is to place a layer on top of an encapsulated cell[61] (Fig. 3a). Based on the consideration above, this layer needs to be highly transmissive for the part of the solar spectrum that is above the bandgap and highly reflective for the part of the solar spectrum that is below the bandgap. Moreover, this layer needs to have near-unity emissivity in the wavelength range of 4–30 μm (Fig. 3b). It has been shown that these requirements can be satisfied with a suitably designed multilayer coating[61]. Theoretical calculations have indicated that such a layer can reduce the temperature of the cell by 5–10 °C, which should translate into an absolute improvement of the cell efficiency by more than half a percentage point. Experimentally, radiative cooling of a solar absorber has been demonstrated by placing a SiO_2 photonic crystal cooling layer on top of a silicon wafer[60] (Fig. 3c). Compared with the silicon wafer by itself, under direct sunlight the cooling layer can reduce the temperature of the silicon wafer by 5 °C without affecting the absorption of sunlight in the silicon wafer. One may envision the placement of such a layer as a retrofit to reduce the temperature of existing cells.

Management of the radiative thermal load of an outdoor coloured object. The concept of radiative cooling in general is connected to the broader context by the need for controlling the radiative thermal load of an outdoor structure, such as a building or an automobile. Given the practical importance and the enormous energy consumption of air-conditioning for these structures, the ability to control the radiative thermal load is of general significance for global energy consumption and human health.

As we have discussed in the section 'Daytime radiative cooling', to minimize the radiative thermal load one can use a near-perfect mirror to reflect all of the sunlight while maximizing thermal emission[22]. Alternatively, to maximize the radiative thermal load, one can use a black object that absorbs all the sunlight but which has minimal thermal radiation[67–71]. However, in many practical situations, the colour of outdoor structures is usually chosen first for functional or aesthetic reasons. The approaches as described above are therefore not directly applicable for controlling the thermal load of coloured outdoor structures since they are either perfectly reflecting or completely black.

For each given colour, there is in fact a very significant tunable range in its radiative thermal load[72,73]. (The range is defined as the difference between the maximum and minimum radiative thermal load that a colour can have in an outdoor environment under direct sunlight.) This arises from both the physical effects of infrared solar absorption and radiative cooling, very similar to the considerations discussed for solar cell cooling, as well as the physiological effects of metamerism (Fig. 3d,e), where different visible spectra may give rise to the same colour response of the human eye. Taking into account all of these effects, it has been determined theoretically that the tunable range exceeds 680 W m^{-2} for all colours and can be as high as 866 W m^{-2} (ref. [72]). Experimentally, it has been demonstrated that two photonic structures with the same pink colour can have their temperatures differ by 47.6 °C under sunlight[72] (Fig. 3f). These structures are either cooler or hotter than a commercial paint of the same colour by over 20 °C. Furthermore, the hotter pink structure is 10 °C hotter than a commercial black paint. These results demonstrate the significant potential of the photonic thermal management of coloured objects. Along this line, a number of photonic systems has been investigated to control the radiative thermal load of coloured objects[74–79].

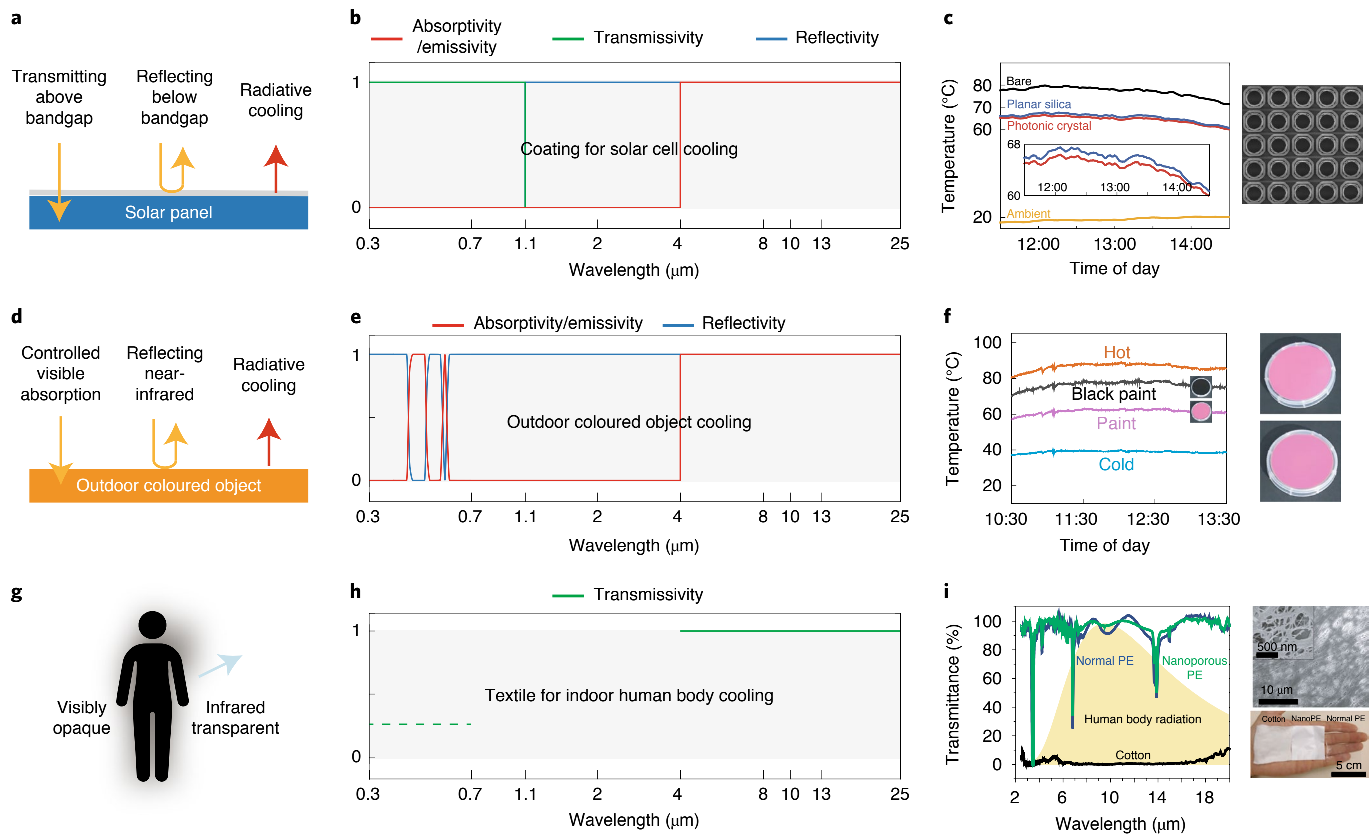

Fig. 3 | Photonic concepts of radiative cooling in solar cells, outdoor coloured objects and textiles. a, Solar cell cooling: an ideal coating for solar cell cooling should have perfect transmission of above bandgap solar radiation, perfect reflection of below bandgap solar radiation and perfect thermal emission for radiative cooling. **b**, The spectral requirement for solar cell cooling. **c**, Experimental demonstration of solar absorber cooling. Photo on the right shows the scanning electron microscope image of the radiative cooler made of SiO_2 photonic crystal. **d**, To minimize the radiative heat load of an outdoor coloured object, the controlled absorption of solar radiation in the visible wavelength range, the perfect reflection of near infrared solar radiation and the perfect thermal emission for radiative cooling are required. **e**, The spectral requirement for outdoor coloured object cooling. **f**, Experimental demonstration of the radiative thermal load management of an outdoor coloured object. Photos on the right show two photonic structures with the same pink colour, but with large (top) and small (bottom) thermal load. **g**, A radiative cooling textile is opaque in the visible wavelength range but transparent in the infrared wavelength range. **h**, The spectral requirement for radiative cooling textiles. **i**, Experimental demonstration of radiative cooling textiles. On the right, the scanning electron microscope image (top) and photo of the cooling textiles (bottom) are shown. PE, polyethylene. Panels adapted with permission from: **c**, ref. [60], PNAS; **f**, ref. [72], Springer Nature Ltd; **i**, ref. [84], AAAS.

In connection to coloured objects where the visible appearance and the radiative thermal load can be independently controlled, another emerging direction in radiative cooling is to achieve visibly transparent radiative coolers. In this direction, there have been a number of attempts to realize transparency and radiative cooling simultaneously[80–82]. These efforts are conceptually connected to some of the concepts in solar absorber cooling[58], such as shown in Fig. 3c, but developed in the different contexts of building thermal management.

Cooling textiles. The radiative cooling concept can also be applied in an indoor environment for cooling the human body[83–88]. A typical indoor environment has a temperature that is lower than the human body. Moreover, in a typical indoor scenario, the radiative heat dissipation in the infrared wavelength range contributes to more than 50% of the total body heat loss. Therefore, facilitating radiative heat transfer from the human body to the ambient environment can contribute significantly to human body cooling. Since we typically wear textiles in an indoor environment, there is a significant opportunity in considering the radiative properties of textiles.

To maximize radiative heat transfer from the human body, the textile should have a high infrared transmissivity in the thermal wavelength range (Fig. 3g,h). Conventional textiles such as cotton are strongly absorptive in the thermal wavelength range, which is therefore suboptimal for the dissipation of body heat. Reference [84] demonstrated a cooling textile that consists of nanoporous polyethylene (Fig. 3i). Polyethylene has a low material loss in both the thermal and visible wavelength ranges. This textile consists of nanopores with sizes comparable to the visible wavelength range. Thus the textile strongly scatters visible light and appears opaque and white. On the other hand, since the size of the nanopores is far smaller than the thermal wavelength, thermal radiation from the human body is not strongly affected by the nanopores and can be transmitted through them. The experiment in ref. [84] covered heating elements with different textiles, and demonstrated that, with the same power input, the heating element that is covered by the cooling textile has a temperature that is 2.7 °C lower compared with the heating element that is covered by cotton.

Cooling textiles have now been made in both woven and nonwoven forms, with different colours and a variety of textile materials[83–92]. For these textiles, other properties that are essential for human comfort, such as wicking capabilities, can be optimized while maintaining the radiative properties[90]. Finally, the cooling textile can be developed to implement the daytime cooling concept

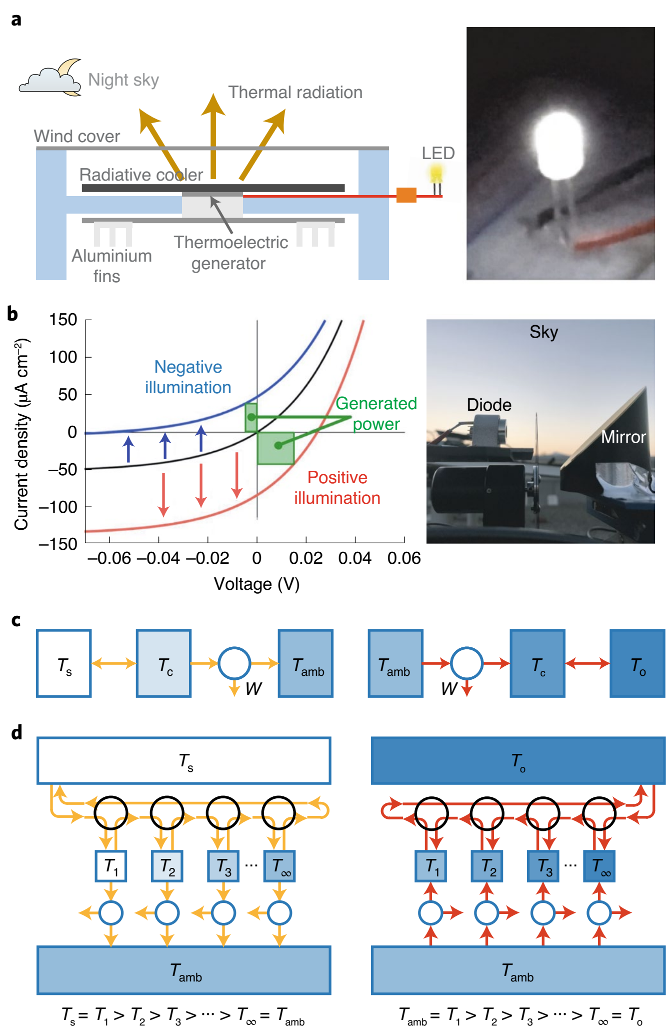

Fig. 4 | Thermodynamic concepts of radiative cooling. a, Radiative cooling can be combined with a thermoelectric generator to generate electricity at night. LED, light-emitting diode. **b**, A low bandgap HgCdTe semiconductor photodiode facing a surface that is colder than the diode, such as the sky, can be used to generate a net electric current. **c**,**d**, The duality relation in the fundamental limits between solar-energy harvesting (left) and the harvesting of outgoing thermal radiation (right), with examples of the blackbody limit (**c**) and the Landsberg limit (**d**). In **c** and **d**, T_s, T_c, T_{amb} and T_o are the temperatures of the sun, the intermediate blackbody, the ambient, and outer space, respectively. The colours of the blue shading indicate the temperature. A lighter colour represents a higher temperature. W is the work extracted from the Carnot engine (blue circle). The black circles in **d** represent circulators that allow reciprocity breaking to enable unidirectionality of the radiative heat flow. Panel **a** adapted with permission from ref. [30], Elsevier.

as discussed in section 'Daytime radiative cooling'. For this purpose, that textiles are strongly emissive in the thermal wavelength range and strongly reflective in the solar wavelength range has been demonstrated[48,49].

Thermodynamic concepts: harvesting outgoing thermal radiation

In the section above we primarily focused on achieving cooling by using radiative heat flow to carry heat away from a hot object. On the other hand, from a fundamental thermodynamic point of view, any heat flux between two reservoirs that have different temperatures can be used to generate usable work. Therefore, one should be able to generate usable work from the outgoing thermal radiation from the Earth to outer space. The magnitude of such outgoing thermal radiation is enormous. For the Earth to maintain an approximately constant temperature, the total power flux in the outgoing thermal radiation must balance that of the incoming solar radiation.

The heat engines used to harvest outgoing thermal radiation have interesting connections and contrasts compared with those for harvesting incoming solar radiation. In both cases, the heat engine is in contact with the Earth as one of the two thermal reservoirs. To harvest incoming solar radiation, the Earth is the low-temperature reservoir. On the other hand, to harvest outgoing thermal radiation, the Earth is the high-temperature reservoir.

As one of the techniques used to harvest the outgoing thermal radiation, since a radiative cooler facing the sky can reach a temperature below the ambient air temperature, one can connect a thermoelectric generator between the radiative cooler and the ambient to generate electricity. Reference [30] demonstrated this concept during the night-time. The radiative cooler consists of an aluminium plate that is painted black. When facing the sky, the cooler can reach a temperature that is a few degrees below the ambient air temperature. A thermoelectric generator, connected to the cooler, is then able to generate electricity with a power density of $25\,\mathrm{mW\,m^{-2}}$ when normalized to the area of the cooler. The generated electricity was used to drive a light-emitting diode, demonstrating that light can be generated from the darkness of the night sky[30] (Fig. 4a). Further simulations have indicated a power density exceeding $1\,\mathrm{W\,m^{-2}}$ may be achievable with existing technologies[25]. These results highlight a renewable approach for night-time electric lighting without the need for an electric grid or energy storage.

The optoelectronic physics of photovoltaic power generation can also be used for harvesting outgoing thermal radiation. When a photovoltaic cell undergoes radiative exchange with a thermal emitter that has a temperature below that of the cell, there is net outgoing thermal radiation from the cell to the emitter, and this net outgoing radiation results in a difference between the generation and recombination current within the cell. Consequently, the cell can generate a net electric current that can be used to drive an external electrical device[93]. Electricity generation in this way has been demonstrated using a HgCdTe photodetector facing the sky[94] (Fig. 4b).

The experimental developments for harvesting outgoing thermal radiation motivate the theoretical development in understanding the associated fundamental limits on the power that can be generated[95–97]. There is in fact a duality relation that maps between the fundamental limits of solar-energy harvesting and the harvesting of outgoing thermal radiation (Fig. 4c,d). The use of the thermoelectric module or the photovoltaic cell discussed above, for example, map to the thermophotovoltaic system and the photovoltaic system for solar energy harvesting. In addition, similar to solar-energy harvesting, the ultimate limit for the power density in harvesting outgoing thermal radiation is defined by the exergy, E, of the outgoing radiation is given by

$$E = T_{\mathrm{amb}} S_{\mathrm{out}} - P_{\mathrm{out}} \tag{6}$$

where S_{out} and P_{out} are the net entropy and power flow in the outgoing radiation, respectively, and T_{amb} is the ambient temperature. Assuming that the emitter is a blackbody (at a temperature $T_{amb} = 300\,\mathrm{K}$), which is radiating to outer space, which is also assumed to be a blackbody (at a temperature $T_o = 3\,\mathrm{K}$), one then has $E = T_{\mathrm{amb}}\left[\frac{4}{3}\sigma\left(T_{\mathrm{amb}}^3 - T_{\mathrm{o}}^3\right)\right] - \sigma\left(T_{\mathrm{amb}}^4 - T_{\mathrm{o}}^4\right)$, which is equal to $153.1\,\mathrm{W\,m^{-2}}$ (ref. [96]). Here, σ is the Stefan–Boltzmann constant. This result is closely analogous to the Landsberg limit for solar-energy harvesting[98] (Fig. 4d). Reaching the Landsberg limit requires the use of non-reciprocal devices as shown in Fig. 4d. Such a theoretical limit significantly exceeds the experimentally observed power density by several orders of magnitude and indicates that there is significant room for future developments. A similar limit has also been established for schemes that seek to simultaneously harvest both sunlight and the outgoing thermal radiation for improving the harvesting efficiency of solar energy[97].

Summary and outlook

In the past few years, radiative cooling has emerged as a significant new direction in renewable energy research, with important potential for wide ranges of applications. In this Review, we have discussed the fundamental photonics and thermodynamics concepts that underlie the processes of radiative cooling. We end this Review by discussing a few emerging directions.

From a photonic design point of view, controlling the emissivity profile is essential for achieving high-performing radiative cooling. As outlined in Fig. 1d, depending on the application objective, the optimal emissivity profile can have complex spectral and angular shapes. Moreover, the variability of the atmosphere at different locations and climate conditions plays a very important role in the radiative cooling process[99–101]. Therefore, when designing a radiative cooler with an optimized emissivity profile, these factors must be considered. Achieving a high-performing radiative cooler that is compatible with large-scale fabrication techniques represents a significant challenge. A promising direction is the application of the computational inverse design technique[102–104] for radiative cooling, which has been applied for radiative coolers that consist of multilayer films[22,61,72,105–107]. Such a technique may find broader application in the design of radiative coolers.

In addition to the absorption and scattering processes, other light–matter interaction processes may have implications for radiative cooling. In this direction, we note the use of fluorescence processes to enhance the effective solar reflectivity of a building for radiative cooling[43,79] and for increasing the production of greenhouse produce[108].

The energy-harvesting processes from outgoing thermal radiation, as discussed in the section 'Thermodynamic concepts: harvesting outgoing thermal radiation', are certainly at a very early stage of development. The experimentally observed power densities[30,94] are several orders of magnitude lower than the theoretical limits[96]. Future improvements may occur through co-optimization of photonic engineered thermal emissivity profiles, heat transfer design and optoelectronic properties of low bandgap semiconductors.

We anticipate significant developments in combining the radiative cooling concept with many other types of renewable energy technology, including solar-energy harvesting and water generation. The harvesting of outgoing thermal radiation may also be used to boost the power density in schemes that harvesting existing heat sources such as human body heat, waste heat and solar thermal heat[97].

More broadly, from a thermodynamic point of view, a low-temperature heat sink is equally as important as a high-temperature heat source in the efficient conversion of heat to work. Existing thermodynamic cycles primarily use the ambient environment as the heat sink. The development of radiative cooling shows that outer space can be used as the heat sink instead. Since outer space has a much lower temperature compared with the ambient, radiative cooling may point to the pathway for systematically improving a wide range of thermodynamic cycles and significantly impact energy technology in general.

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Competing interests

S.F. owns shares in Skycool Systems, which seeks to commercialize some of the radiative cooling technology discussed here.

Additional information

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