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Discussion

# Radiative cooling, what's next?

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A R T I C L E I N F O

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A B S T R A C T

Radiative coatings make use of omnipresent surface thermal radiation for passive cooling of objects without consuming energy or emitting greenhouse gases, and are a promising energy-saving strategy at scale to address the climate change problem. In the last decade, thanks to advances in photonics and micro/nano-fabrication technologies, we have witnessed the emergence of high-performance radiative coatings with hundreds of different designs. In this work, the development timeline of radiative coatings is summarized and potential research directions in this field are analyzed. Existing challenges and opportunities, especially for passively switchable radiative coatings, are discussed. We hope this short review promotes radiative coating materials and products for serving the sustainability of our society in various markets such as buildings, vehicles, and space objects.

Climate change is severely affecting everyone on this planet in a way that has never been crueler before. Crises such as extreme weather, sea-level rise, and saltwater intrusion result in a large number of "climate refugees" and cause huge economic loss [1]. Human activities that burn fossil fuels are among the main drivers of climate change via the generation of greenhouse gases. We are at a stage where adaption to climate consequences is required almost everywhere to protect people, homes, and ecosystems. The Paris Agreement, a legally binding international treaty on climate change, was adopted at the twenty-first session of the Conference of the Parties (COP21) of United Nations (U.N.), with a goal to limit global warming to well below 2 degrees Celsius, compared to pre-industrial levels, by reaching global peaking of greenhouse gas emissions [2]. Therefore, it is extremely urgent to develop and deploy renewable energies and energy-saving technologies to realize long-term sustainability.

Radiative coatings, or cool roofs when applied to buildings, are among the most promising green technologies with a massive potential to regulate temperature and reduce energy consumption for air conditioning in buildings [3]. Note that here the word "radiative coating" is used to represent all types of products applied to the surface of an object to radiatively manage its temperature, and could be in the form of a solid covering or a fast-drying paint. This is of key importance as, according to published statistics [4,5], more than 50% of the total energy in residential buildings in many countries is consumed on space heating and cooling. The radiative coating technology can be traced back to the 20th century when researchers developed a straightforward but effective measure that a thermally emissive coating passively (i.e., without activation or energy input from the user) cool terrestrial objects [6]. Based on Planck's law of blackbody radiation, those objects lose heat by emitting mid-infrared (MIR) electromagnetic waves into the cold outer space that is at approximately 3 K [3]. In addition, sunlight absorption of those coatings is minimized to reduce solar heating for continuous diurnal cooling (Fig. 1A). As a result, radiative coatings for static cooling were realized to reduce space-cooling energy consumption [7,8]. Here "static" means environment-independent properties and hence time-independent performance of the coating. Similar physical process is also developed and exploited in biological systems [9].

Though the physics is clear, static radiative coatings could only deliver low net cooling power since the electromagnetic properties of conventional materials are far from optimum for this purpose. This situation changed in the 2010s thanks to advances in photonic physics and micro/nano fabrication technologies. Since 2014, high-performance radiative coating materials and devices started to emerge, mostly featuring artificial, deep-subwavelength photonic structures [7,10]. In just a few years, variable static radiative coatings with scalable production were invented for passive cooling of building [8,11–13,16] or even human body [14]. For example, novel structural materials [8], nano/microparticle-embedded flexible coating [11,15], hierarchically structured porous polymer [12], and pigmented coating [17] were reported that show superior radiative cooling performance.

Nevertheless, like in all technologies, further innovations are needed and will emerge for radiative coatings. The above implementations are

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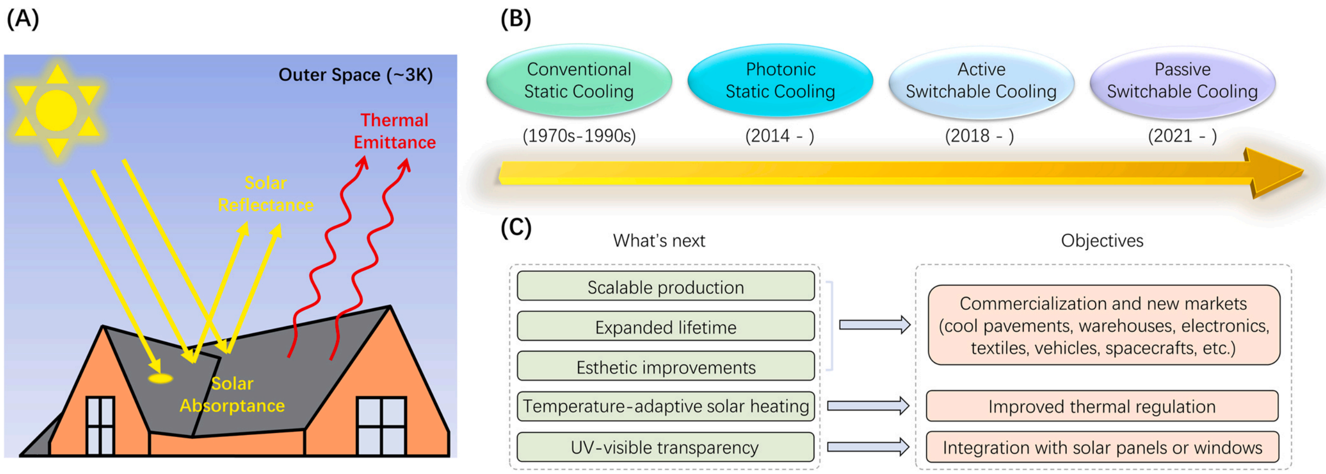


**Fig. 1.** Development history and "what's next" in radiative cooling. (A) Schematic diagram of the radiative cooling process of a roof for building thermal regulation; (B) Brief timeline of the development of radiative cooling; (C) Future research directions and their influence, especial for passively switchable radiative coatings.

all excellent static coolers to use in heat waves, and they continue to radiate heat even in cold weather when space heating is required. In other words, those static radiative coatings exacerbate space-heating energy consumption and their year-round energy savings are significantly compromised in climate zones with large day-to-night or summer-to-winter temperature variations. This challenge was tackled by switchable, in contrast to static, radiative coolers, whose thermal emissivity is switched "ON" at high ambient temperatures and "OFF" at low ambient temperatures. Such "ON/OFF" switching was demonstrated using active approaches, including electrical driving [18], mechanical actuation [19], and flip-over structures [20].

To eliminate the energy or activation demands during the "ON/OFF" switching process, passively switchable radiative coatings were invented very recently, with successful demonstration of temperature-adaptive radiative coolers based on "smart" materials [21–23]. Those materials sense the environment condition (for example, temperature) and automatically adjust their material properties (electromagnetic, mechanical, etc.) accordingly. In most cases, the thermal emissivity of such passively switchable radiative coatings switches automatically and reversibly in response to changes in the ambient temperature, requiring no energy input nor intervention from the user. Simulations have confirmed that, in climate zones where a wide temperature variation exists around the year, passively switchable radiative coatings as a roof material deliver more year-round source energy saving compared to all existing roof materials with static radiative properties [21]. Therefore, it is safe to say that passively switchable coatings and static radiative coatings could be used to reduce energy consumption for buildings in temperate and tropic climates, respectively.

As commercialization efforts have already started for advanced static radiative coatings [24], future development in this field may primarily lie in passively switchable coatings. To fully unleash the potential of radiative cooling coatings, five potential research directions could be envisioned.

First and foremost, scalable production of passively switchable radiative coatings is the key to commercialization and large-scale deployment. Expensive micro/nanofabrication technologies, such as photo- and electron-beam lithography, atomic layer deposition, and dry etching should be avoided. Future radiative coatings are preferably manufactured without vacuum tools, and use of any delicate nanostructures and movable mechanical elements should be maximally avoided. High-throughput fabrication of static radiative coatings offer inspirations for tackling engineering challenges in scaling up switchable radiative coatings. The price of passively switchable radiative coatings per unit area should be eventually lowered to a level comparable to those of commercial cool-roof products [25].

Second, the stability and durability of the materials and structures should be paid high attention in the development. Radiative coatings on roofs face inevitable environmental erosions in their whole lifecycle, such as rain and snow precipitation, wind, ultraviolet (UV) exposure, dusts, vibration and mechanical damage, extreme high/low temperatures, etc. All these factors impact the materials and structures within the radiative coatings, leading to a gradual degradation in their thermal regulation performance. It is preferred that radiative coatings could maintain 80% of their original thermal regulation performance after 3 years of deployment. It is suggested to integrate and utilize materials with high robustness and resistance to environmental influences. In addition, firm adhesion to roof tiles, high hydrophobicity, and low flammability are also imperative requirements for perennial application.

Third, esthetic consideration is vital for successful commercialization as customers will not be impressed by products with dull or disturbing appearances. Though pigments are universally used in conventional roof paintings, it is not straightforward to directly incorporate them into radiative coatings without affecting the solar absorptance and thermal emittance. Several static radiative coatings were reported with variable colors and simultaneously high cooling capacities, but customized colors in passively switchable radiative coatings are still rare.

Furthermore, as passively switchable radiative coatings have already been realized in the lab, their thermal regulation capacity by solely adjusting thermal emissivity will soon be maxed out. Efforts are encouraged to be devoted to adding the function of temperature-adaptive solar absorption onto the temperature-adaptiveness of thermal radiation. To be specific, an ideal smart coating should be dual-band switchable: (1) At high temperatures, the coating exhibits simultaneously low solar absorptivity and high thermal emissivity for maximized cooling capacity; and (2) at low temperatures, its solar absorptivity is automatically switched "ON" while its thermal emissivity is switched "OFF" for maximal heating and heat retention. The switching temperature could be customized according to the local climate and user requirements. Annual thermal regulation and the resultant energy saving of such dual-band smart coatings would be significantly improved.

Last but not the least, the integration of radiative coatings onto windows or solar panels is a promising research field. Photovoltaic efficiency drops as the temperature increases, hence static radiative coatings that cover solar panels can prevent overheating in a passive way. To achieve this goal, the UV–visible transmittance of the coatings should be high, so that sunlight is able to pass through and arrive at the solar panels underneath for electricity generation [26]. Similarly, passively switchable radiative coatings with UV–visible transparency helps objects covered with solar panels to achieve year-round energy saving.

Thanks to advances in micro/nanofabrication [27], 21st-century researchers discovered new paths to boost the thermal regulation performance of static radiative coatings towards a level where 20th-century researchers could only dream of. With the holistic viewpoint of year-round energy saving, researchers moved forward and have developed passively switchable radiative coatings, so that people living in diverse climate zones, not just the tropics, could benefit from this green technology. Radiative coatings in a variety of forms and with diverse functionalities will play an important role in energy saving in a wide range of applications, including but not limited to building roofs [3,28], windows [29] and walls [30], as well as cool pavements [31] and warehouses [32], spacecrafts [33], textiles [34], vehicles [35], and electronics [36]. We hope this short review could inspire researchers and engineers to make more groundbreaking innovations in the field of radiative coatings to help sustain a more energy-efficient and environment-friendly society.

## Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Author J.W. is a Chair on the Advisory Board of Next Energy.

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