energies

MDPI

Perspective

Perspectives on the Applications of Radiative Cooling in Buildings and Electric Cars

N. S. Susan Mousavi [1,*] and Brian Azzopardi [2,3]

1 School of Physics, Institute for Research in Fundamental Sciences (IPM), Tehran P.O. Box 19395-5531, Iran
2 MCAST Energy Research Group, Institute of Engineering and Transport, Malta College of Arts, Science and Technology (MCAST), Main Campus, Corradino Hill, PLA 9032 Paola, Malta; brian.azzopardi@mcast.edu.mt
3 The Foundation for Innovation and Research—Malta, 65 Design Centre Level 2, Tower Road, BKR 4012 Birkirkara, Malta
* Correspondence: s.mousavi@ipm.ir

Abstract: Cooling energy consumption is a major contributor to various sectors in hot climates with a significant number of warm days throughout the year. Buildings account for 40% of total energy consumption, with approximately ∼30–40% of that used for cooling in geographical areas such as Iran. Energy demand for cooling is an important factor in the overall energy efficiency of electric mobility. Electric vehicles (EVs) consume ∼30–50% of energy for the air conditioning (AC) system. Therefore, the efficient management of the cooling demand is essential in implementing energy-saving strategies. Passive radiative cooling is capable of providing subambient cooling without consuming any energy. This article reviews potential applications of passive radiative cooling in reducing cooling energy for buildings. It also provides a rough estimate of the amount of energy saved when applying a radiative cool roof to a model building. It is shown that by using radiative cool materials on roofs, the share of electricity usage for cooling can be reduced to 10%, leading to a reduction in cooling load by 90%. Additionally, the potential use of radiative cool coats of various types for different EV components, such as shell/body, windows, and fabrics, is introduced. Although the prospects of the design and engineering of radiative cooling products appear promising for both buildings and EVs, further investigations are necessary to evaluate scalability, durability, and performance based on factors such as geography and meteorology.

Keywords: radiative cooling; passive cooling; cooling energy consumption; electric vehicle (EV); building energy efficiency

check for updates

Citation: Mousavi, N.S.S.; Azzopardi, B. Perspectives on the Applications of Radiative Cooling in Buildings and Electric Cars. *Energies* **2023**, *16*, 5256. https://doi.org/10.3390/en16145256

Academic Editor: Jae-Weon Jeong

Received: 19 May 2023
Revised: 29 June 2023
Accepted: 4 July 2023
Published: 9 July 2023

1. Introduction

The International Energy Agency's report on World Energy Vision, identifies energy production as the primary cause of anthropogenic air pollution across the globe. Therefore, the report highlights the need for improving energy efficiency as a solution to this problem [1]. Air pollution is mainly caused by fossil-fuel combustion (such as coal, oil, and natural gas), the major source of energy generation in many countries [2]. Fossil fuel combustion results in the emission of toxic air pollutants, such as nitrogen oxides (NO_x)and carbon dioxide (CO_2), which are responsible for global environmental issues, such as air and water pollution, injustice and inequalities, and the major threat to children's health [3].

Many countries around the world have implemented macro-policies to tackle energy-related issues, with a primary focus on enhancing energy efficiency and promoting clean and renewable energy sources [4]. For instance, Iran and Malta, despite having different geographical locations, share similar regional climate characteristics. Iran has an extremely continental climate, mostly arid or semi-arid, with weather typical of the Middle East. The Law of Energy Reform (implemented in 2011) and Clean Air Act (implemented in 2017) [5] are examples of policies that Iran has adopted. Malta experiences a Mediterranean climate, and as part of its efforts to address energy-related issues, it has implemented various policies, such as the Energy Law (enforced since 2011) and National Energy Efficiency Action Plans NEEAP (enforced since 2012).

According to data, steam power plants, with a low efficiency of 36%, which are operated by fossil fuels (gasoline, mazut or natural gas), generate approximately 90% of the electricity in Iran [6]. According to statistics, two-thirds of the fuels are inefficiently consumed, which is significantly contributing to air pollution. Further, when compared to the United States (12%), Europe (19.7% with a goal of 32% by 2030) [7], and Australia (35.9% with a target of 82% by 2030) [8], the share of renewable energies is negligible in Iran, at less than 1% [9].

Iran is currently facing two major crises regarding water and energy, as evidenced by statistical data from 2019 to 2020. These data highlight a significant 35.5% reduction in rainfall, a 27% decrease in the volume of water entering reservoir dams, and a 29.98% decline in hydroelectric power plant energy production. Additionally, the energy industry has observed an annual average increase of 5% in energy consumption, with the highest shares coming from households at 32.4%, and the industrial sector at 36.3%. Moreover, there was a reported deficit of over 21,000 megawatts (MW) in energy production in 2021.

In Malta, the total energy supply (TES) shows that natural gas and oil have an equal contribution of 50%, which together account for approximately 80% of emissions of 2 Mt of CO_2. With 94% dependence on imported fossil fuels, Malta has one of the highest import dependencies in the EU. According to reports, until 2016, Malta had higher greenhouse gas emissions than the annual target, which covers transportation, buildings, agriculture, and waste sectors [10]. In 2020, electricity consumption reached about 2.43 TWh, representing a 140% increase from 1999 [11].

In the following, we offer insight on how passive radiative cooling techniques can be utilized to reduce the need for cooling energy in areas with hot and dry climates such as Tehran (Iran) and Malta. We will examine the potential impact of passive radiative cooling strategies on two major electricity consumer sectors—buildings and electric vehicles (EVs). The performance of radiative cooling, a zero-energy technique for cooling a surface, depends on various geographical factors, such as meteorological conditions (humidity and sky conditions) and diurnal or nocturnal applications. Daytime radiative cooling typically encounters more challenges than nighttime cooling due to direct solar irradiation. However, for nocturnal use, regions with Mediterranean and temperate climates (characterized by low humidity, large diurnal temperature fluctuations, mostly clear skies, and minimal cloud cover) are the most suitable locations for adopting passive radiative cooling [12].

Section 2 covers the working principle of radiative cooling for heat removal from a surface and an enclosure. The section also explores the potential use of radiative cooling as a means to reduce cooling load in buildings, with Section 2.1 discussing a preliminary study based on data from model buildings monitored by the Energy Department of the Municipality. The findings show the promising potential of the use of radiative passive cooling to reach the set goals of the energy efficiency law and regulations. Section 2.2. investigates the potential use of passive cooling in electric vehicles (EVs). According to data, the electric vehicle (EV) market is expected to reach EUR 16.18 million in 2023 with a projected annual revenue rate growth of 15.45% (2023–2028)in Malta [13]. As air conditioning (AC) accounts for a significant portion of total energy consumption in EVs, various strategies have been explored to minimize AC power consumption while maintaining passenger comfort levels. For instance, efforts toward the performance optimization of AC components, heat load reduction, and zonal cooling have been reported [14].

2. Passive Heat Removal from Surfaces and Enclosures

With a net positive thermal energy accumulated in an enclosure, such as a building or a vehicle, the inside temperature increases. To achieve and maintain the thermal comfort level for the occupants in a building or the passengers of a vehicle, temperature control devices are used that consume power to remove the excess thermal load. One method of lowering the cooling load on an enclosure is passive radiative cooling. This refers to a thermal management method, where engineered materials with selective emissivity of infrared spectra within the atmospheric window (8 to 13 microns) and reflectivity of visible solar spectra can significantly decrease the heat load on a surface while consuming zero energy [15]. The proportionality of the thermal energy due to solar irradiation (0.2–2.5 µm) is approximately 57% for the infrared (IR) spectra (700–2500 nm), 38% for visible (VS) spectra (400–700 nm), and 3% for ultra violet (UV) spectra (300–400 nm). Since the IR spectra is responsible for the majority of the heat load, many efforts related to passive cooling energy management have focused on restricting the IR energy absorbed by a surface [16].

A passive radiator can reduce the temperature of a surface down to subambient temperatures by limiting the contribution of the infrared on the heat gain [17]. Radiative cooling products include paint coatings [18], sprays, cooling wood [19], cool fabrics [20], and radiative cooler systems. Traditional cooling methods typically require the consumption of energy, water, or chemicals, which contribute to the increasing demand for energy, particularly electricity, and result in excessive water consumption and negative environmental impacts caused by the use of synthetic fluids. As a result, passive cooling strategies are gaining interest. Radiative coolers can reach up to 100 watts per square meter in ideal conditions but geography affects performance [12,16]. Li et al. developed a superior cooling wood material with superior characteristics compared to natural wood in terms of its continuous cooling capability, mechanical strength, and sustainability. They showed that this material, when applied to the roofs and sides of buildings in the US, could save up to 40% of energy depending on the type of building and geographic location, taking into account the climate region [19].

Daytime radiative cooling faces limitations due to the direct solar irradiation as well as the parasitic heat gain by a surface. To facilitate diurnal cooling, nano-structures such as photonic structures [21], nanoparticle-doped materials [22] and metamaterials [23] have been engineered, providing high reflectivity plus high emissivity. As an example, the top surface of the radiative material exposed to sunlight can be coated with a light-reflecting layer. This additional layer does not impede the radiation from the primary layer but instead functions similarly to a transparent material in the atmospheric window. Zhu et al. designed a dual-side radiative coat applicable to cover the roof of enclosures, such as a building or a car. The photonic-engineered transparent film (consisting of a hot mirror and radiant barrier) was integrated with a temperature-regulated enclosure, and a power saving of up to 63% was experimentally demonstrated [24].

The cool coats exchange the energy with the cold space outside the atmosphere through thermal emission. This passive strategy, which is the way the Earth cools itself, can be applied in a wide range of domestic, commercial and industrial applications [25]. The working principle of a radiative cool coat applied onto the top surface of an enclosure can be seen in Figure 1. The energy balance on the control surfaces 1 and 2 (CS1 and CS2) is

$$\begin{aligned} q''_{sky} + q''_{solar} &= q''_{rad.CS1} + \underbrace{q''_{conv.outside} + q''_{cond.}}_{q''_{nonradiative}} \\ q''_{cond.} + q''_{rad.encl.} &= q''_{rad.CS2} + q''_{conv.inside} \end{aligned} \tag{1}$$

where q''_{sky}, q''_{solar}, $q''_{rad.CS1}$, and $q''_{rad.CS2}$ denote, respectively, absorbed radiative heat fluxes from the sky and the solar irradiation, and thermal emissions from CS1 and CS2. $q''_{cond.}$ and $q''_{conv.}$, which are nonradiative terms, represent the heat exchange via conduction and convection. The net energy gain by the enclosure, causing its temperature $T_{encl.}$ to rise, is

$$q''_{net} = q''_{rad.CS2} + q''_{conv.inside} - q''_{rad.encl.} + q''_{loss} \tag{2}$$

where q''_{loss} represents the heat exchange between the walls and the surroundings:

$$\begin{aligned}
q''_{rad.CS1} &= \varepsilon_1 \sigma T_1^4 \\
q''_{rad.CS2} &= \varepsilon_2 \sigma T_2^4 \\
q''_{rad.encl.} &= \varepsilon_2 \sigma T_{encl.}^4 \\
q''_{cond.} &= k_{roof} \frac{T_1 - T_2}{d} \\
q''_{conv.outside} &= h_{out}(T_1 - T_{ambient}) \\
q''_{conv.inside} &= h_{in}(T_2 - T_{encl.})
\end{aligned} \tag{3}$$

Comparing Equations (1) and (2), $q''_{net} \simeq q''_{cond.}$ if the q''_{loss} is negligible, which is the case for the enclosures whose walls are well insulated. Therefore, by estimating the heat flux by conduction through the roof, a rough estimate of the cooling load reduction can be obtained if a radiative cool coating is applied onto the roof.

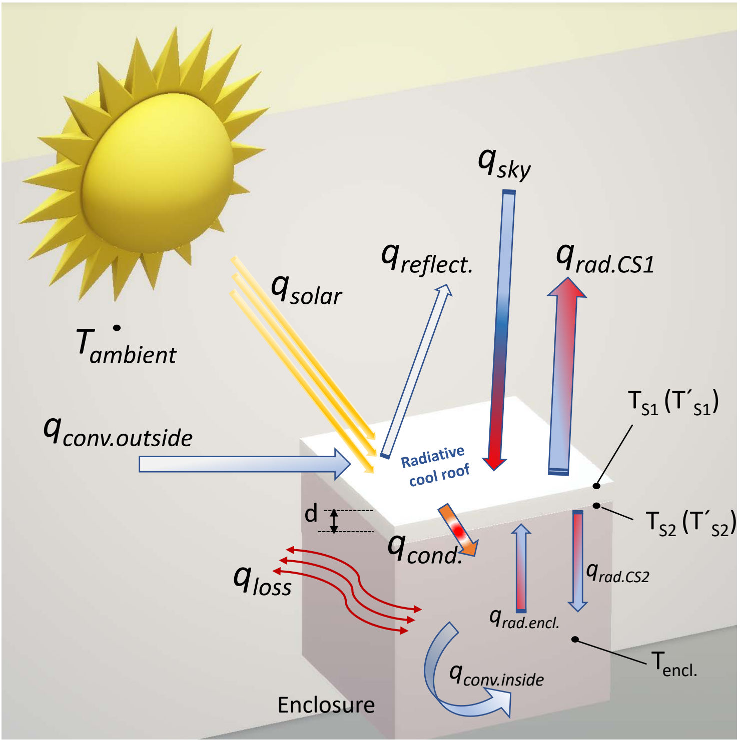


Figure 1. Working principle of radiative cooling. The enclosure's roof is covered by the radiative cooling coat. A cool coat is a selective surface that is characterized by high reflectivity and high emissivity within the atmospheric window of 8–13 µm. The temperature of a surface covered by a cool coat can be reduced to subambient temperatures. The temperature of an enclosure can be reduced due to the reflection and emission by the interior and exterior surface.

2.1. Reducing the Cooling Load of Buildings

Buildings are responsible for consuming 40% of energy on average, and contribute up to 40% of greenhouse gas emissions, depending on the contribution of fossil fuels in electricity generation. Hence, it is imperative to introduce policies and legislation aimed at optimizing energy consumption in buildings in order to reduce their environmental impact. A study conducted in a tropical region of Australia explored the effects of using a cool coat to cover a residential building's roof on its energy efficiency. Since cooling devices consume 30% of total household energy and 57% during peak consumption, researchers examined the impact of 36 different combinations of roof materials and color samples in order to identify optimal strategies for reducing cooling load through roof renovation. The simulation results consistently demonstrated decreased peak load in all cases following the application of cool coats [26].

According to statistical data, in climates similar to Tehran, cooling energy accounts for an average of 30–40% of total energy usage. In the southern regions of Iran, however, this figure is about four times higher than the average, which significantly exceeds the typical consumption. Considering the large number of warm days experienced throughout the year in Iran, the effective management of cooling energy would result in a substantial reduction in building energy consumption [27]. To address this issue, the City of Tehran conducted a comprehensive study on energy consumption in its buildings and implemented a suitable plan, which includes measures such as the insulation and optimization of HVAC systems, among others.

We conducted a previous investigation on an area of improvement in building energy management [28]. The study demonstrated that cool coatings have the potential to enhance the performance of evaporative coolers (ECs), which are widely used for cooling in buildings across Iran. During the summer season, a considerable share of urban households in Iran, specifically 70.9%, use evaporative cooler (EC) devices to cool their residential units. On average, these households operate their ECs for approximately 12 h a day. The total number of ECs used in Iran amounts to roughly 22 million and is projected to increase annually by 3%.

Considering a commercial cool paint capable of lowering the temperature of a surface by 30% [29], potential savings in water and electricity consumption were estimated. If the cool paint is applied to the body of an evaporative cooler (EC), it could lower the body temperature, resulting in (a) significantly increasing the efficiency of the EC during the hot days when temperatures exceed 35 °C (which occurred on 112 days in 2021), (b) limiting water evaporation up to 65%, and (c) reducing the operational hours, thereby decreasing the electricity consumption.

Wang et al. applied a scalable metamaterial radiative cooling film to the roof of a commercial large-scale warehouse in a hot summer and warm winter climate zone in China to reduce cooling energy consumption.The double-layered film was 200 µm thick, with the top layer made of a metamaterial having an emissivity of 0.91 within the atmospheric window of 8-13 µm, while the bottom layer had a silver coating with a reflectivity of 0.92. It was shown that the average daily cooling electricity consumption for the warehouse of 8208 m^2 was decreased by 44.36% when compared to the conventional steel roof (448.6 kWh were reduced to 249.6 kWh) [30]. Also the roof temperature and the fluctuation in the warehouse temperature were significantly decreased. With such a cool coat, considering the temperatures of the exterior roof surface and the interior room temperature near the roof, the heat flux entering the enclosure can be calculated as

$$\frac{q''_C}{q''_{RC}} = \frac{k_C}{k_{RC}} \left(\frac{\int_{0:00}^{23:59} (T_{S1}(t) - T_{S2}(t))\, dt}{\int_{0:00}^{23:59} (T'_{S1}(t) - T'_{S2}(t))\, dt} \right) \tag{4}$$

where T_{S1} and T_{S2} represent the temporal temperatures of the exterior and interior of the conventional roof, respectively, while T'_{S1} and T'_{S2} correspond to the temporal temperatures of the exterior and interior of the radiative cool (RC) roof (see Figure 1). q''_C, q''_{RC}, k_C and k_{RC} represent the heat flux and thermal conductivity of the conventional roof and those of the RC roof, respectively. We adopted the corresponding k_C value for the roof of the model building used as a community center in Tehran from [31]. The radiative cool coat has low thermal conductivity as compared to that of the conventional roof materials. However, the exact values depend on the materials they are made of. For instance, values of 0.06 [24] and 0.28 [32] have been reported for the engineered RC. To ensure a conservative estimation, the latter k value is selected. The temporal distribution of temperatures was adopted from Figure 7 in reference [30]. We obtain

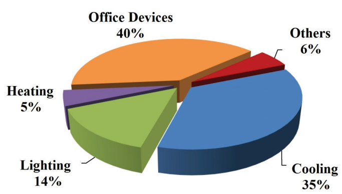
$$\begin{gathered} \frac{q''_C}{q''_{RC}} = \frac{0.8}{0.28} \left(\frac{28.28 - 19.42}{20.57 - 18.11} \right) = 10.3 \\ q''_{RC} = 9.71\%\, q''_C \end{gathered} \tag{5}$$

It is seen that the overall heat flux is significantly reduced during 24 h. At the peak temperature occurs at around 13:30 pm with the corresponding temperature values of T_{S1}, T_{S2}, T'_{S1}, and T'_{S2}, which are provided in reference [30], we obtain the ratio of heat fluxes as

$$\begin{gathered} \frac{q''_C}{q''_{RC}} = \frac{0.8}{0.28}\left(\frac{55\ ^\circ\mathrm{C}-26.2\ ^\circ\mathrm{C}}{34.1\ ^\circ\mathrm{C}-23.1\ ^\circ\mathrm{C}}\right) = 7.56 \\ q''_{RC} = 13.24\%\, q''_C \end{gathered} \tag{6}$$

The major contribution of the roof to cooling load is significantly hindered as the surface temperatures are decreased. Wang et al. extended the aforementioned validated model to model buildings in different climate zones and compare a cool roof (reflectivity 0.7-emissivity 0.85) with an engineered radiative cool (RC) roof (reflectivity 0.92-emissivity 0.91). It was shown that the annual cooling energy saving and the amount of cooling power saving per unit area for a cool roof (a radiative cool roof) can reach up to 14.5% and 3.8 kWh/m^2 (22.4% and 5.9 kWh/m^2) in the model buildings in Greenville, USA. In Mexico, corresponding values showed better performance for the cool roof and the RC roof, with savings of 44.2% and 6.9 kWh/m^2 (65.2% and 10.1 kWh/m^2), respectively.

By adopting the saving values corresponding to Greenville (USA), we can calculate the potential savings on a model building in Tehran, which is used as a community center. The electricity shares and distribution of the cooling load can be seen in Figure 2. As shown, cooling has the second-largest contribution to the electricity usage profile. (22.4% and 5.9 kWh/m^2).



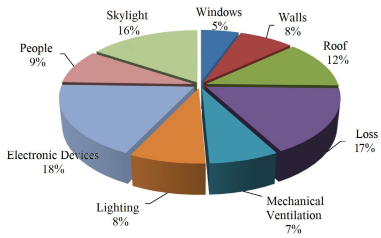


Figure 2. (**Left**) Shares of electricity usage in the community center building which is being monitored under energy regulations by the Municipality of Tehran. Cooling, which accounts for 35% of the total electricity consumption, is the second-largest contributor. (**Right**) The distribution of the cooling load with the roof accounting for 12% of the total cooling load.

Based on the data provided in Table 1 for annual cooling electricity consumption (37,206 kWh/m^2), and percentage share of the roof (12%), the electricity usage for cooling associated with the roof is calculated as $\frac{37{,}206\times 12\%}{270}\left(\frac{\mathrm{kWh}}{\mathrm{m}^2}\right) = 16.54$. Applying the cool roof (annual cooling energy saving of 14.5%, cooling power saving per unit area of 3.8 kWh/m^2) to the model building can reduce the total electricity usage and result in savings per unit area. Consequently, the proportion of the cooling load attributed to the roof is expected to decrease. For a cool roof:

$$\frac{37{,}206 - \overbrace{14.5\%(37{,}206)}^{31{,}811.13}}{270}\left(\frac{\mathrm{kWh}}{\mathrm{m}^2}\right) / \overbrace{(16.54-3.8)}^{12.74}\left(\frac{\mathrm{kWh}}{\mathrm{m}^2}\right) = 9.25\% \tag{7}$$

Similarly if the RC roof (annual cooling energy saving of 22.4%, cooling power saving per unit area of 5.9 kWh/m^2) is applied onto the roof, we obtain

$$\frac{37{,}206 - \overbrace{22.4\%(37{,}206)}^{28{,}871.86}}{270}\left(\frac{\mathrm{kWh}}{\mathrm{m}^2}\right) / \overbrace{(16.54-5.9)}^{10.64}\left(\frac{\mathrm{kWh}}{\mathrm{m}^2}\right) = 10\% \tag{8}$$

It is seen that covering the roof with a cool roof or a RC roof can decrease the contribution of the conventional roof from 12% to 9.25% and 10%, respectively. The findings are tabulated in Table 1.

Table 1. Energy saving for the model building. A community center, under the energy efficiency monitoring protocol by the Tehran Municipality. Two types of modified roof are considered: a cool roof (reflectivity 0.7—emissivity 0.85) (annual cooling energy saving of 14.5%, cooling power saving per unit area of 3.8 kWh/m^2), and a radiative cool (RC) roof (reflectivity 0.92—emissivity 0.91) (annual cooling energy saving of 22.4%, cooling power saving per unit area of 5.9 kWh/m^2).

Roof		Electricity Consumption (kWh/m^2)	Electricity Saving				Improved Share in Total Cooling Load	
			Cool Roof		Radiative Cool Roof			
			% 14.5	kWh/m^2 3.8	% 22.4	kWh/m^2 5.9	Cool Roof	Radiative Cool Roof
Share in Total Cooling Load	12%							
Annual Cooling Electricity Consumption (kWh)	37,206	16.54	31,811.13	12.74	28,871.86	10.64	9.25%	10%
Roof Area (m^2)	270							

Radiative cool roofs are typically more effective for structures with a large ratio of roof area to cooling surfaces, such as warehouses or villas, than for high-rise buildings. The saving values utilized in our analysis were derived from simulation results for a building in Greenville (USA), which represent the lowest values among the six regions studied in [30]. This approach prevents the overestimation of potential savings. Considering Tehran's predominantly hot and dry climate with clear skies, the actual saving values are expected to be higher; however, further research is required to verify this.

2.2. Reducing the Cooling Load of Electric Vehicles

The application of radiative cooling methods in electric vehicles (EVs) to manage the cooling power demand is still in the early stages of laboratory research. While the concept of passively cooling surfaces and enclosures can be utilized to model a stationary vehicle, many factors must be accounted for when considering cooling loads for a moving vehicle.

The thermal comfort level within a vehicle's cabin is affected by six primary parameters, including air temperature and relative humidity, radiant temperature, activity level, and clothing materials of the passengers [33]. Various components contribute to the total heat energy load on the cabin of an electric vehicle (EV), including metabolic heat load, glass heat load, and shell/body heat load. The shares attributed to windows and the shell are among the largest. According to studies, the share of heat load for EV windows ranges from 37.3% to 52.6%, while that for the shell ranges from 20.3% to 42% [14]. Table 2 presents various potential passive methods for reducing heat load from EV components such as the vehicle's windows and shell. The table also includes radiative cool coatings designed to act as selective radiative and broadband absorptive materials which are potentially suitable for a vehicle.

2.2.1. Shell/Body

Heo et al. designed a bidirectional thermal emitter (*J*ET) that exhibits high emission of thermal energy from the top surface and high absorption on the bottom surface. If the engineered (*J*ET) is attached facing outward on the top surface of an enclosed space, such as a stationary vehicle, it can passively remove heat trapped due to the greenhouse effect in enclosures. This is because the bottom surface absorbs thermal input in a broad spectral range. Further, the top surface remains cooler than the ambient temperature, as it emits heat to space. It was shown that the (*J*ET) could lower the temperature of an enclosure, such as a stationary automobile environment by 4 °C when compared to a conventional radiative cooler. Therefore, it offers an advanced passive cooling solution for the simultaneous surface and space cooling of enclosures [34].

When assessing the heat load in the cabin, in addition to restricting the IR energy received by the surfaces of an EV (i.e., an enclosure), the greenhouse effect is also important in increasing the inside temperature. The temperature of an enclosure is affected by the temperature of its surfaces as well as the trapped air inside it, which results in a greenhouse effect. To mitigate this effect, it was shown that engineered (*J*ET) for the walls of an enclosure can draw heat from the inner space by broadband absorption/emission. By utilizing engineered surfaces that can emit IR energy outwards to the sky from the superstrate and absorb VS by the substrate, energy removal from an enclosure can be improved significantly [34]. However, the Janus emitter is applicable to the enclosures with higher internal temperature than their roof but not for air-conditioned spaces that are cooler inside than their roofs during summertime. The design of a photonic-engineered material that was enhanced by the color-preserving radiative cooling (ECRC) system by Zhu et al. offered a promising performance [24]. The ECRC can also take decorative factors into consideration. The results showed a temperature decrease of 5.5 °C/ 4.0 °C/ 2.3 °C/ 5.8 °C in enclosures with green, red, white, and black radiative roofs, respectively, compared to conventional roofs on a normal summer day. The potential cooling power saving was reported up to 63%, with a prospect of 81% for an ideal ECRC.

2.2.2. Windows

The effects of the various types of glazed glasses (windows) characterized by reflection and emission properties, on the EV cabin heat load and the impact of the vehicle range were assessed [35]. Three types of glasses were compared—regular glass materials, a high-performance glass available in the market, and a theoretically ideal radiative glass, in various geographical locations across the USA—to evaluate the effects of meteorological factors. The results showed that using commercial glazed glass and ideal radiative glass resulted in an increase in EV range by 33.1 miles and up to 92.5 miles, respectively, when compared with traditional glass. Additionally, the study found that the geographical location significantly influenced the results. Another study demonstrated that the use of solar reduction glass windows on a mid-size EV could decrease the surface temperature and cooling consumption by 2 °C and 20%, respectively [36].

2.2.3. Fabrics for Interior of the Vehicle

Since cabin materials, such as the seats' fabric, could be important in determining the value of radiant temperature, radiative cool fabrics are also enlisted in Table 2. In general, the design of high-performance absorber/emitter materials suitable for the interior sections of an EV should also be considered. Various types of radiative cool textiles [37,38], such as silver-coated polyamide textile [39], have mostly been designed for personal thermal management and can be considered for the interior upholstery of an EV. Lv et al. suggested a cover designed by radiative cool materials to avoid the overheating of parked vehicles [40].

Table 2. Potential passive cooling techniques for reducing cooling load in electric vehicles (EVs). Innovative radiative cooling products for shell/body, windows, and cabin.

Shell/Body †	Windows ‡	Seat's Fabric
(i) Transparent radiative cooler that can be combined with paint. Daytime cooling ∼ 10.1 °C–14.4 °C [41].	(i) IR transparent metamaterial for windows, ∼7 °C cooling [42].	(i) Coating on cotton fabrics with high durability, for daytime cooling with reflectivity of 90% and emissivity of 92%, corresponding to ∼5.4 °C cooling. [43].

Table 2. *Cont.*

Shell/Body †	Windows ‡	Seat's Fabric
(ii) Janus Emitter; selective emission, broadband absorption. ∼6 °C subambient cooling from a surface, ∼4 °C subambient space cooling (from an enclosure) [34].	(ii) A transparent dual-layer film for daytime radiative cooling. ∼6 °C subambient cooling of an interior space [44]	(ii) A cover (fabric) for parked vehicles keeps cabin air temperature within comfortable range [40].
(iii) Engineered photonic-based metamaterial as an enhanced color-preserving radiative cooling (ECRC) system. Lowering the exterior surface temperature by ∼ 21 °C, enclosure temperature up to ∼ 5.8 °C, saving of cooling power up to 63% [24].	(iii) A scalable thermochromic smart window with tunable emissivity of long-wave infrared with potential use for windows [45]	(iii) Wrapping films with potential use as fabric/covers ∼5.6 °C subambient cooling [46].

† Share of heat load is ∼37.3–52.6% [14]; ‡ Share of heat load is ∼20.3–42% [14].

3. Conclusions

Passive radiative cooling coats can help mitigating cooling load in hot climates, such as in Tehran (Iran) and Malta, particularly during the summer season. Possible areas of radiative cooling applications in buildings as well as in electric vehicles for energy savings were reviewed. For instance, a comparison was made between the electricity consumption savings of a conventional cool roof and an engineered radiative cool (RC) roof for a building in Tehran based on a rough, yet conservative, estimate. The findings showed that the heat flux through the roof can be reduced by approximately 90%, and the contribution of the roof in cooling load can be dropped below 10% if the RC roof is considered. In structures where the roof area accounts for a larger portion of the overall cooling load, applying radiative cooling may have a more compelling economic justification.

Nocturnal passive radiative cooling uses materials that are less expensive and simpler to engineer than those used in daytime cooling. Therefore, nighttime radiative coolers can be considered for villas or commercial buildings, resulting in a significant reduction in cooling at night to manage energy consumption. However, the effectiveness of radiative cool coats depends heavily on regional climate conditions and must be tailored to specific geographical conditions to optimize their impact on energy savings. As a result, further research is needed to identify suitable radiative cooling materials.

For electric vehicles (EVs), several radiative cooling products have been proposed for the shell/body, windows, and interior fabrics. However, to determine the practical benefits in terms of reduced electricity consumption for air conditioning, battery charge savings, and increased range (in kilometers), it is necessary to conduct detailed studies that take into account pivotal parameters, such as vehicle size, vehicle condition both while stationary and in motion, as well as regional and meteorological conditions, including humidity and sky conditions.

Author Contributions: Conceptualization, N.S.S.M. and B.A.; methodology, N.S.S.M. and B.A.; investigation, N.S.S.M.; writing—original draft preparation, N.S.S.M.; writing—review and editing, N.S.S.M. and B.A.; supervision, B.A.; funding acquisition, B.A. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported in part by the European Commission H2020 TWINNING Networking for Excellence in Electric Mobility Operations (NEEMO) Project under Grant 857484. Also, the findings in this article are partly based on the comprehensive research supported by the Tehran Urban Research and Planning Center for the project entitled "Investigation of Innovative and Eco-Friendly Approaches to Reduce Buildings Energy Consumption: A Case Study in Tehran" (2022-in Persian) [31].

Data Availability Statement: The provided data for the model building in this article is based on a non-publicly published report by the Municipality of Tehran (written in Persian) and are available upon formal request.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

EV	Electric vehicle
EC	Evaporative cooler
AC	Air conditioning
VS	Visible spectra
IR	Infrared spectra
RC	Radiative cool

References

1. Air Quality—Multiple Benefits of Energy Efficiency—Analysis. International Energy Agency (IEA). 2016. Available online: https://www.iea.org/reports/multiple-benefits-of-energy-efficiency/air-quality (accessed on 10 May 2023).
2. McDuffie, E.; Martin, R.V.; Spadaro, J.V.; Burnett, R.; Smith, S.J.; O'Rourke, P.; Hammer, M.S.; van Donkelaar, A.; Bindle, L.; Shah, V.; et al. Source Sector and Fuel Contributions to Ambient PM 2.5 and Attributable Mortality Across Multiple Spatial Scales. *Nat. Commun.* **2021**, *12*, 3594. [CrossRef] [PubMed]
3. Perera F. Pollution from Fossil-Fuel Combustion is the Leading Environmental Threat to Global Pediatric Health and Equity: Solutions Exist. *Int. J. Environ. Res. Public Health* **2017**, *15*, 16. [CrossRef] [PubMed]
4. US Environmental Protection Agency (EPA). 12 March 2013. The Sources and Solutions: Fossil Fuels. Overviews and Factsheets. (Last Updated on 2023). Available online: https://www.epa.gov/nutrientpollution/sources-and-solutions-fossil-fuels (accessed on 10 May 2023).
5. The Law of Energy Reform, Legislated and Implemented on 2011. Available online: https://rc.majlis.ir/fa/law/show/789793 (accessed on 10 May 2023).
6. Share of Steam Power Plants in Electricity Generation in Iran, IRNA. Available online: https://en.irna.ir/news/84718089/Iran-s-thermal-power-generation-grows-by-8 (accessed on 10 May 2023).
7. Renewable Energy-Directive, Targets and Rules. European Commision. Available online: https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules_en (accessed on 10 May 2023).
8. Clean Energy Council. Clean Energy Australia Report. Available online: https://www.cleanenergycouncil.org.au/resources/resources-hub/clean-energy-australia-report (accessed on 10 May 2023).
9. Iran: Power Production Share by Source 2020. Statista. Available online: https://www.statista.com/statistics/1236239/iran-distribution-of-electricity-production-by-source/ (accessed on 20 June 2023).
10. Energy. Towards an Energy Union. A Summary of Full Version Contained in the 3rd Energy Union Report (November 2017) Malta. Available online: https://energy.ec.europa.eu/index_en (accessed on 6 May 2023).
11. Malta—Countries & Regions. IEA. Available online: https://www.iea.org/countries/malta (accessed on 10 May 2023).
12. Lu, X.; Xu, P.; Wang, H.; Yang, T.; Hou, J. Cooling potential and applications prospects of passive radiative cooling in buildings: The current state-of-the-art. *Renew. Sustain. Energy Rev.* **2016**, *65*, 1079–1097. [CrossRef]
13. Electric Vehicles—Malta | Statista Market Forecast. Retrieved 23 March 2023. Available online: https://www.statista.com/outlook/mmo/electric-vehicles/malta (accessed on 5 July 2023).
14. Jose, S.S.; Chidambaram, R.K. Electric Vehicle Air Conditioning System and Its Optimization for Extended Range—A Review. *World Electr. Veh. J.* **2022**, *13*, 204. [CrossRef]
15. Granqvist, C.; Hjortsberg, A.; Eriksson, T. Radiative cooling to low temperatures with selectivity IR-emitting surfaces. *Thin Solid Films*. **1982**, *90*, 187–190. [CrossRef]
16. Bijarniya, J.; Sarkar, J.; Maiti, P. Review on passive daytime radiative cooling: Fundamentals, recent researches, challenges and opportunities. *Renew. Sustain. Energy Rev.* **2020**, *133*, 110263. rights and content%0A. [CrossRef]
17. Lim, X. The Super-Cool Materials That Send Heat to Space. *Nature* **2019**, *577*, 18–20. [CrossRef]
18. Mandal, J.; Yang, Y.; Yu, N.; Raman, A. Paints as a scalable and effective radiative cooling technology for buildings. *Joule* **2020**, *4*, 1350–1356. [CrossRef]
19. Li, T.; Zhai, Y.; He, S.; Gan, W.; Wei, Z.; Heidarinejad, M.; Dalgo, D.; Mi, R.; Zhao, X.; Song, J.; et al. A Radiative Cooling Structural Material. *Science* **2019**, *364*, 760–763. [CrossRef]
20. Peng, Y.; Chen, J.; Song, A.Y.; Catrysse, P.B.; Hsu, P.; Cai, L.; Liu, B.; Zhu, Y.; Zhou, G.; Wu, D.S.; et al. Nanoporous polyethylene microfibres for large-scale radiative cooling fabric. *Nat. Sustain.* **2018**, *1*, 105–112. [CrossRef]
21. Raman, A.; Anoma, M.; Zhu, L.; Rephaeli, E.; Fan, S. Passive radiative cooling below ambient air temperature under direct sunlight. *Nature* **2014**, *515*, 540–544. [CrossRef]
22. Huang, Z.; Ruan, X. Nanoparticle embedded double-layer coating for daytime radiative cooling. *Int. J. Heat Mass Transf.* **2017**, *104*, 890–896. [CrossRef]
23. Zhai, Y.; Ma, Y.; David, S.N.; Zhao, D.; Lou, R.; Tan, G.; Yang, R.; Yin, X. Scalable-manufactured randomized glass-polymer hybrid metamaterial for daytime radiative cooling. *Science* **2017**, *355*, 1062–1066. [CrossRef]
24. Zhu, Y.; Luo, H.; Yang, C.; Qin, B.; Ghosh, P.; Kaur, S.; Shen, W.; Qiu, M.; Belov, P.; Li, Q. Color-Preserving Passive Radiative Cooling for an Actively Temperature-Regulated Enclosure. *Light Sci. Appl.* **2022**, *11*, 122. [CrossRef] [PubMed]

25. Zhao, B.; Hu, M.; Ao, X.; Xuan, Q.; Pei, G. Spectrally selective approaches for passive cooling of solar cells: A review. *Appl. Energy* **2020**, *262*, 114548. [CrossRef]
26. Miller, W.; Crompton, G.; Bell, J. Analysis of Cool Roof Coatings for Residential Demand Side Management in Tropical Australia. *Energies* **2015**, *8*, 5303–5318. [CrossRef]
27. Statistics on Energy Consumption for the City Household Customers in Iran. 2011. Available online: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.amar.org.ir/Portals/0/Files/fulltext/1390/n_energy_90.pdf (accessed on 10 May 2023).
28. Mousavi, N.S. Susan. Radiative Cooling for Energy Efficiency in Buildings of Tehran. In Proceedings of the 13th Mediterranean Conference on Power Generation, Transmission; Distribution and Energy Conversion Institution of Engineering and Technology: Hybrid Conference, Valletta, Malta, 7–9 November 2022; pp. 508–513. [CrossRef]
29. Rain Guard Water Sealers SP-2001 Cool Coat White Thermal Barrier. Available online: https://www.amazon.com/Rainguard-International-SP-2005-Acrylic-Thermal/dp/B0733K2YZ4?ref_=ast_sto_dp&th=1&psc=1 (accessed on 25 November 2022).
30. Wang, N.; Lv, Y.; Zhao, D.; Zhao, W.; Xu, J.; Yang, R. Performance Evaluation of Radiative Cooling for Commercial-Scale Warehouse. *Mater. Today Energy* **2022**, *24*, 100927. [CrossRef]
31. Fakharan, Z.; Dabirian, A.; Mousavi, N.S.S. Innovative and Technological Eco-Friendly Approaches for Reducing Energy Consumption in Buildings; A Review and Analysis. *Danesh Shahr Magazine*. **2023**. (In Persian) [CrossRef]
32. Leroy, A. High-performance subambient radiative cooling enabled by optically selective and thermally insulating polyethylene aerogel. *Sci. Adv.* **2019**, *5*, eaat9480. [CrossRef] [PubMed]
33. Simion, M.; Socaciu, L.; Unguresan, P. Factors which Influence the Thermal Comfort Inside of Vehicles. *Energy Procedia* **2016**, *85*, 472–480. [CrossRef]
34. Heo, S.-Y.; Lee, G.J.; Kim, D.H.; Kim, Y.J.; Ishii, S.; Kim, M.S.; Seok, T.J.; Lee, B.J.; Lee, H.; Song, Y.M. A Janus emitter for passive heat release from enclosures. *Sci. Adv.* **2020**, *6*, eabb1906. [CrossRef] [PubMed]
35. Penning, A.K.; Weibel, J.A. Assessing the Influence of Glass Properties on Cabin Solar Heating and Range of an Electric Vehicle Using a Comprehensive System Model. *Appl. Energy* **2023**, *339*, 120973. [CrossRef]
36. Ozeki, Y.; Harita, Y.; Hirano, A.; Nishihama, J. *Evaluation on the Solar Reduction Glass in an Electric Vehicle by Experimental Measurements in a Climate Chamber*; SAE Technical Paper 2014-01–0703; SAE Technical Paper: Warrendale, PA, USA, 2014. [CrossRef]
37. Shin, S.; Chen, R. Cool Textile. *Joule* **2021**, *5*, 2258–2260. [CrossRef]
38. Peng, Y.; Cui, Y. Advanced Textiles for Personal Thermal Management and Energy. *Joule* **2020**, *4*, 724–742. [CrossRef]
39. Xie, X.; Liu, Y.; Zhu, Y.; Xu, Z.; Liu, Y.; Ge, D.; Yang, L. Enhanced IR Radiative Cooling of Silver Coated PA Textile. *Polymers* **2021**, *14*, 147. [CrossRef]
40. Lv, Y.; Huang, A.; Yang, J.; Xu, J.; Yang, R. Improving cabin thermal environment of parked vehicles under direct sunlight using a daytime radiative cooling cover. *Appl. Therm. Eng.* **2021**, *190*, 116776. [CrossRef]
41. Kim, M.; Lee, D.; Son, S.; Yang, Y.; Lee, H.; Rho, J. Visibly Transparent Radiative Cooler under Direct Sunlight. *Adv. Opt. Mater.* **2021**, *9*, 2002226. [CrossRef]
42. Jin, Y.; Jeong, Y.; Yu, K. Infrared-Reflective Transparent Hyperbolic Metamaterials for Use in Radiative Cooling Windows. *Adv Funct Mater.* **2023**, *33*, 2207940. [CrossRef]
43. Zhong, S.; Yi, L.; Zhang, J.; Xu, T.; Xu, L.; Zhang, X.; Zuo, T.; Cai, Y. Self-Cleaning and Spectrally Selective Coating on Cotton Fabric for Passive Daytime Radiative Cooling. *Chem. Eng. J.* **2021**, *407*, 127104. [CrossRef]
44. Lei, M.-Q.; Hu, Y.-F.; Song, Y.-N.; Li, Y.; Deng, Y.; Liu, K.; Xie, L.; Tang, J.-H.; Han, D.-L.; Lei, J.; et al. Transparent radiative cooling films containing poly(Methylmethacrylate), silica, and silver. *Opt. Mater.* **2021**, *122*, 111651. [CrossRef]
45. Wang, S.; Tengyao, J.; Yun, M.; Ronggui, Y.; Gang, T.; Yi, L. Scalable Thermochromic Smart Windows with Passive Radiative Cooling Regulation. *Science* **2021** *374*, 1501–1504. [CrossRef]
46. Park, C.; Park, C.; Park, S.; Lee, J.; Choi, J.; Kim, Y. S.; Yoo, Y. Passive Daytime Radiative Cooling by Thermoplastic Polyurethane Wrapping Films with Controlled Hierarchical Porous Structures. *ChemSusChem* **2022**, *15*, e202201842. [CrossRef] [PubMed]