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Radiative sky cooling of silicon solar modules: Evaluating the broadband effectiveness of photonic structures

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ABSTRACT

Photovoltaic solar cells are designed to efficiently absorb solar photons but convert only a limited proportion of them into electricity. Under real operating conditions, the remaining energy causes solar modules to heat up to 50–60 °C, which is detrimental to their power conversion efficiency and lifetime. In recent years, there has been a growing interest in the so-called radiative sky cooling strategy. This approach consists in optimizing the thermal radiation of cells or modules—with the help of photonic structures—by taking advantage of the atmospheric transparency in the 8–13 range. In this paper, we present an in-depth analysis of radiative sky cooling applied to silicon based photovoltaic modules. A simulation of a preliminary design of a photonic structure for possible radiative sky cooling of a module is also proposed.

Radiative sky cooling (RSC) has a significant theoretical benefit,[1,2] and practical applications[3–10] are starting to emerge in the field of crystalline silicon (c-Si) photovoltaic (PV) devices. The literature proposes various photonic approaches that aim to modify the thermal emissivity profile, thereby enhancing RSC. In our recent paper,[1] we have demonstrated that the ideal thermal emissivity of solar modules beyond the bandgap should correspond to the profile shown in Fig. 1. As we can see, this allows a double thermal benefit by: (i) reflecting all photons in the parasitic solar absorption (PSA) range, which corresponds to the range 1.1–4 μm and (ii) enhancing thermal emission in the mid-infrared (MIR) range, that is for wavelengths $>4\,\mu$m. Furthermore, maintaining good absorption in the PV conversion (0.3–1.1 μm) range is essential to ensure that cooling is not at the expense of photovoltaic performance. These claims are in good agreement with those available in the literature. Among the growing number of proposals, some of them come close to the desired properties.[4,7–9,11] The prospective work dedicated to multi-junction devices has even started to emerge.[12]

Despite the fact that some approaches are very promising, several aspects must be carefully addressed for the resulting technologies to be effective. In particular, there is still a need of clear methodological guidelines in order to comprehensively assess the benefit of a given photonic approach. First and foremost, current studies are sometimes carried out on devices that do not have the properties of a solar module.[3,6,10,14,15] In fact, the thermal emissivity of the latter should be used as the starting point.[16] Notably, the emissivity of a conventional c-Si module is quite different from that of a c-Si solar cell.[17] In the MIR range, the thermal emissivity depends only on the module cover glass. (An optimization at the cell scale is, thus, ineffective.) In the PSA range, the thermal emissivity depends partly not only on the cell but also on the glass and the ethylene-vinyl acetate (EVA). Second, the impact of a change in the module's emissivity profile on its power conversion efficiency is not always thoroughly assessed. In simulations, this requires to cover the entire PV-PSA-MIR range and to make use of a coupled physical model for the PV module. Importantly, some studies neglect the influence of one or more of the PV,[13,18] PSA,[9,19] or MIR[2,13] ranges despite the fact that all three ranges influence the thermal and electrical behavior. As for physical modeling, some studies do not include a coupling between the thermal and electrical properties[13] or do not assess the benefit on the electrical properties at all.[5,6,20]

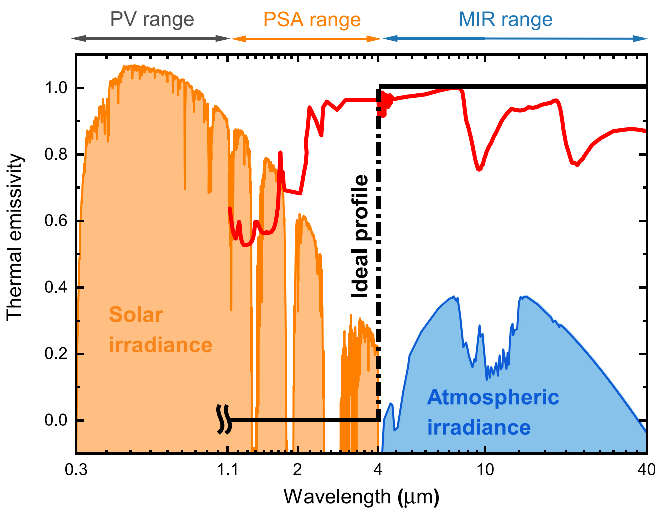

FIG. 1. Incoming solar and atmospheric irradiance. The absorbed irradiance (blue) corresponds to the US standard atmosphere. The red line depicts the real thermal emissivity profile of silicon-based solar modules (data extracted from Ref. 13). The black line of the graph shows the ideal emissivity for RSC.

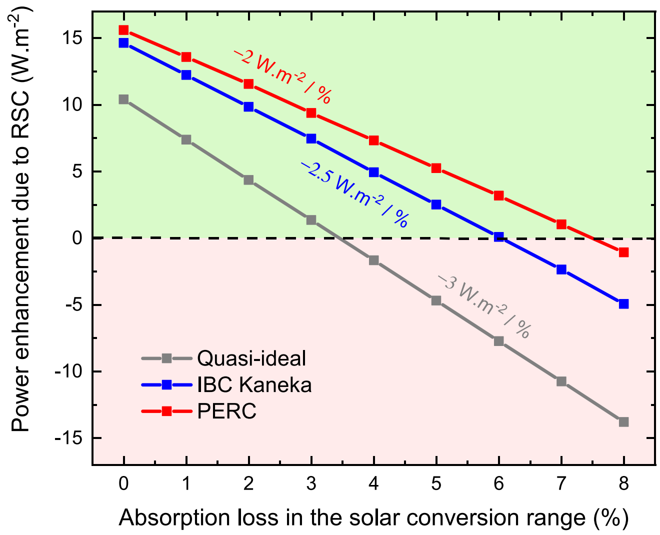

FIG. 2. Electrical power gain obtained thanks to an ideal emissivity profile as a function of the absorption loss in the PV range. Results are given for the quasi-ideal, the IBC Kaneka, and the PERC devices.

The objective of the present study is twofold. First, we investigate the importance of considering the PV conversion range in the analysis of RSC. To this extent, some practical guidelines are introduced to evaluate the ability of a given photonic approach to enhance thermal performance while also maintaining good electrical conversion efficiency. This complements the previous theoretical work,[1] now providing a clear picture over the entire PV-PSA-MIR range. On this basis, we then propose a preliminary design of a photonic structure. Its benefit on thermal and electrical performance is comprehensively quantified to serve as a benchmark methodology for this purpose.

To evaluate the impact of a change in emissivity on the electrical and thermal behaviors, it is of interest to consider several devices. Thus, we consider two commercial solar modules and one ideal module with respect to their external luminescence efficiency Q_e^{lum} and absorption in the PV range α_{PV}:

1. Quasi-ideal: $Q_e^{lum} = 1.0$, $\alpha_{PV} = 0.96$;
2. IBC Kaneka:[21,22] $Q_e^{lum} = 1.6.10^{-2}$, $\alpha_{PV} = \mathrm{EQE}$;
3. PERC:[23] $Q_e^{lum} = 1.6.10^{-4}$, $\alpha_{PV} = \mathrm{EQE}$.

The term EQE relates to the external quantum efficiency of the aforementioned references. Solar modules with different properties are considered, because this changes their electro-thermal behavior, and so does the impact of a change in the thermal emissivity. For instance, Q_e^{lum} strongly affects both the power conversion efficiency and its sensitivity to increased temperature.[24] The physical model used to evaluate the electro-thermal behavior is based on our self-consistent model developed in our previous work.[1] Unless otherwise stated, reference environmental conditions are used (solar spectrum AM1.5G, standard U.S. atmosphere, 15 °C, no wind). More details about the physical model and the EQE can be found in the supplementary material.

Figure 2 summarized the power enhancement due to an increase in the RSC as a function of the power loss due to a lower light absorption in the PV range. The calculation takes into account a thermal emissivity profile equal to 75%[16] in the MIR range and equals to 20% in the PSA range.[13]

At first, for the quasi-ideal cell, the benefit of RSC is canceled when the absorption in the PV range is decreased by only 3%. More generally, the electrical power loss is of about $-3\,\mathrm{W\,m^{-2}}$/%, i.e., per each percent of absorption loss in the PV conversion range. Such a power decrease is high compared to the previously established power increase resulting from the improvement in the thermal emissivity profile:[1] $+0.2\,\mathrm{W\,m^{-2}}$/% in the MIR range (i.e., a 15 times smaller sensitivity) and $+0.1\,\mathrm{W\,m^{-2}}$/% in the PSA range (30 times smaller sensitivity). For the more realistic scenarios (IBC Kaneka and PERC cells), the benefit of the RSC is canceled for a slightly higher deterioration of absorption in the PV range (6% and 7.5%, respectively). This is likely because of their lower efficiency, which increases their operating temperature. Thus, their electrical power enhancement due to RSC is higher. Additionally, they also show a slightly lower sensitivity to the electrical power loss per each percent of absorption: $-2.5\,\mathrm{W\,m^{-2}}$/% for the IBC Kaneka case and $-2\,\mathrm{W\,m^{-2}}$/% for the PERC case. Overall, this highlights that the constraint on the absorption in the PV range is higher for solar cells with good efficiency.

Based on the previous results, more general quantitative criteria for the optimization of radiative properties of silicon modules can be proposed. These criteria noted f_{PSA} and f_{MIR} establish a link between the electrical power gain associated with an improvement in the emissivity in the PSA or MIR ranges and the electrical power loss related to the absorption degradation in the PV conversion range. We define these two quantities as follows:

$$f_{PSA} = \frac{\delta\varepsilon_{PSA}\downarrow}{\delta\alpha_{PV}\uparrow} = \left(\frac{\delta P_{elec}}{\delta\alpha_{PV}\uparrow}\right)\cdot\left(\frac{\delta P_{elec}}{\delta\varepsilon_{PSA}\downarrow}\right)^{-1},$$

$$f_{MIR} = \frac{\delta\varepsilon_{MIR}\downarrow}{\delta\alpha_{PV}\uparrow} = \left(\frac{\delta P_{elec}}{\delta\alpha_{PV}\uparrow}\right)\cdot\left(\frac{\delta P_{elec}}{\delta\varepsilon_{MIR}\downarrow}\right)^{-1}.$$

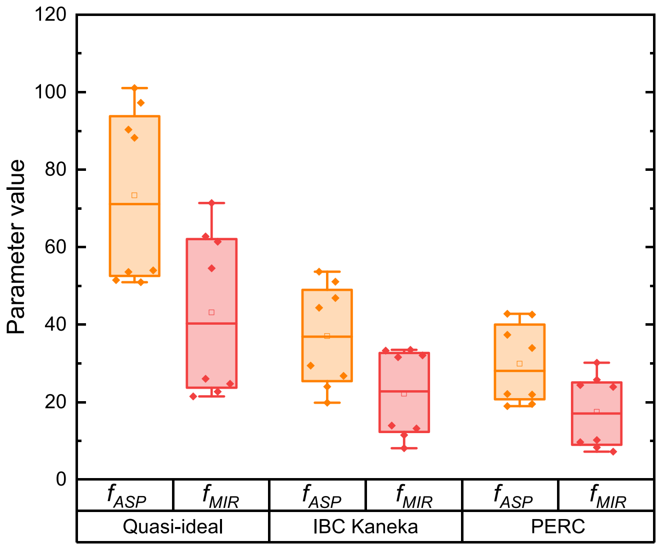

FIG. 3. Values of f_{MIR} and f_{PSA} in different boundary conditions. Each point is calculated by a set of three conditions: $T_{amb} = (15, 25)^{\circ}$ C, h = (5, 15) W m^{-2} K^{-1}, I_{sun} = (500, 1000) W m^{-2}.

Here, P_{elec} is the electrical power, $\overline{\alpha_{PV}}$ is the average absorptivity in the PV conversion range, $\overline{\varepsilon_{PSA}}$ is the average emissivity in the range of parasitic solar absorption, and $\overline{\varepsilon_{MIR}}$ is the average emissivity in the MIR range. The signs ↑ and ↓ indicate an increase and a decrease, respectively. The derivatives with respect to a given spectral range are calculated by keeping the properties constant in the other ranges. Thus, the average degradation $\Delta\overline{\alpha_{PV}}$ of the tolerable PV absorption during a reduction of parasitic absorption $\Delta\overline{\varepsilon_{PSA}}$ is given by $\Delta\overline{\varepsilon_{PSA}} = f_{PSA}.\Delta\overline{\alpha_{PV}}$. Similarly, the average $\Delta\overline{\alpha_{PV}}$ degradation of the tolerable PV absorption during an increase in the MIR emissivity $\Delta\overline{\varepsilon_{MIR}}$ is given by $\Delta\overline{\varepsilon_{MIR}} = f_{MIR}.\Delta\overline{\alpha_{PV}}$. With the help of environmental conditions, namely, ambient temperature, solar irradiation, and wind velocity, it is possible to calculate the mean value of f_{MIR} and f_{PSA}.

The box plot given in Fig. 3 illustrates the obtained results. When comparing the three scenarios, the general trend is consistent with what might be expected from Fig. 2: the quasi-ideal scenario exhibits the highest constraint on the PV range, while the PERC case has the lowest constraint. The IBC is slightly more sensitive to the PV range with an average value of about 20 for f_{MIR} and 35 for f_{PSA}. This shows that the sensitivity to the PV range should be of special concern especially when improving the emissivity in the PSA range. In fact, any (average) improvement of emissivity in the PSA range must be accompanied by a 35 times smaller decrease in the (average) PV absorption range. Otherwise, there will be no benefit to electrical power. Note that environmental conditions change the values of f_{PSA} and f_{MIR}, leading to a large dispersion of the values. However, the most notable effect is due to wind velocity (value of h). As the latter increases, the baseline operating temperature decreases and, therefore, the electrical power is less affected by any change in radiative cooling properties. Hence, the values of f_{PSA} and f_{MIR} increase with wind velocity. This effect can be seen in Fig. 3, where two groups of data points are visible in each case.

Note that these results assume that the decrease in PV absorption is not correlated with absorption by non-active materials in the module. The latter phenomenon would induce a higher operating temperature for the same decrease in PV absorption and, thus, an increase in sensitivity.

The importance of such a broadband analysis and the high sensitivity to a small decrease in the PV absorption is illustrated through a preliminary design of the photonic structure for RSC. Among several approaches proposed in the literature at air/glass or glass-EVA interfaces, such as metallo dielectric filters, transparent conductive oxide based hot mirrors, or full dielectric hot mirrors, the last one clearly appears as the most able to limit the decrease in the PV absorption. As derived from the multilayer dielectric mirror located at the air/glass interface of a silicon module proposed by Li *et al.*,[13] which decreases its temperature by 5.7 °C, 32 layers based on two materials, TiO_2 and SiO_2, have been designed under normally incident light using a transfer matrix method[25] given the ideal absorption/emissivity profile of Fig. 1. The final thickness is about 1446 nm. The resulting spectra, shown in Fig. 4, are used to calculate the electrical and thermal behaviors in the three scenarios formerly introduced.

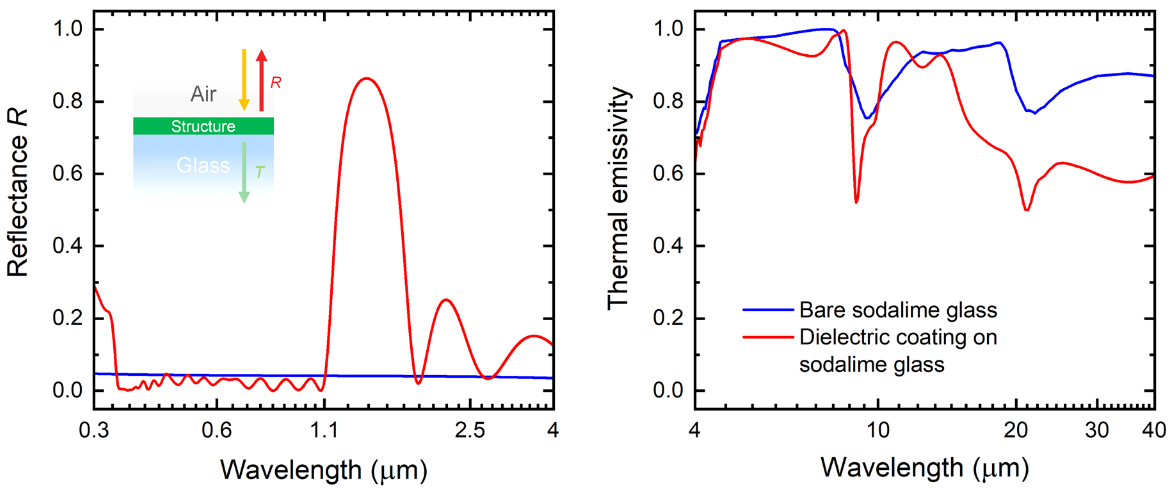

FIG. 4. Spectral reflectance of the module glass (left) and module's MIR thermal emissivity (right), calculated with (red) and without (blue) the photonic structure.

TABLE I. Electrical and thermal behaviors of the solar module due to RSC with two optimization scenarios.

Cell	ΔT (°C)		ΔJ_{gen} (mA cm^{-3})		ΔP_{elec} (W m^{-2})	
	PV-PSA[a]	BB[b]	PV-PSA	BB	PV-PSA	BB
Quasi-ideal	−5.3	−3.7	+0.3	+0.3	+5.2	+4.1
IBC Kaneka	−5.1	−3.6	+0.4	+0.4	+5.6	+4.7
PERC	−4.6	−3.0	+0.4	+0.4	+5.8	+4.6

[a]PV and PSA spectral domains.
[b]PV and PSA and MIR spectral domains (broadband).

More precisely, as reported in Table I, if this calculation only takes into account the PV absorption and PSA reflection ("PV-PSA" in Table I), the module temperature and electrical performances are significantly enhanced. However, these enhancements are reduced if the MIR part of the spectrum is taken into account. This shows the importance of performing a broadband calculation to estimate the benefit of a given photonic structure. This is due to the decrease in the thermal emissivity induced by the filter mainly above 13 μm (see Fig. 4). Overall, the proposed photonic structure still allows it to decrease the operating temperature and to enhance the electrical power.

In conclusion, we have investigated the use of radiative cooling to improve the operating temperature of silicon-based modules. The main results can be summarized as follows:

- It is mandatory to include the PV part of the spectrum for any optimization procedure of the module RSC, i.e., the optimization of the absorption/emission beyond the bandgap. In fact, even of a few percent degradation of solar absorption will cancel any benefit of enhanced RSC.
- We have introduced a new criterion that quantifies and links absorptivity and reflectivity different parts of the solar spectrum and solar module thermal emission. This criterion serves as a guideline to determine if a given structure is worth studying in more detail.
- It was revealed that the reflectivity profile in between [λ_{gap}−4 μm] is strongly linked with any modification in the module emissivity.
- Based on our criterion, we have found a new photonic structure, which simultaneously enhances RSC and maintains electrical conversion performance. Notably, we have highlighted the importance of the broadband calculation in order to assess its benefits.

The takeout message is that we can no longer optimize the optical properties of the module only on the infrared part of the spectrum. A thorough quantification of the photon balance over the entire PV-PSA-MIR range is mandatory. Finally, future research is oriented toward the extension of this analysis to other proposed solutions for the RSC.

See the supplementary material for the physical model and the EQE of the selected solar cells. In addition, we provide the details of the dielectric coating material, thickness, and structure.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

J. Dumoulin: Investigation (lead); Writing – review & editing (equal). **E. Drouard:** Investigation (equal); Writing – review & editing (equal). **M. Amara:** Investigation (equal); Supervision (equal); Writing – original draft (equal).

DATA AVAILABILITY

The data that support the findings of this study are available within the article.

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