Passive radiative cooling materials integrated in renewable energy technologies for enhanced performance

Juliana Jaramillo-Fernandez[1,2,*], *Gerardo* Silva-Oelker[3], *David* Astrain[4]

[1]Heat Engines Department, Universitat Politècnica de Catalunya, 08028, Barcelona, Spain
[2]Cooling Photonics S.L., 08022, Barcelona, Spain
[3]School of Engineering, Universidad Mayor, 7500994, Santiago, Chile.
[4] Engineering Department, Public University of Navarre, 31006 Pamplona, Spain

Abstract. Radiative cooling involves decreasing the temperature of a body by emitting infrared radiation. When the heat loss from the emitting surface exceeds the heat gain, e.g. from the sun or the atmosphere, a passive net cooling effect occurs without the need for electricity or other power sources. Integrating radiative cooling materials with other renewable energy technologies such as photovoltaics and thermoelectric generators represents a promising frontier in sustainable energy systems. In this study, we explore the strategic utilization of the net cooling effect resulting from radiative cooling materials to enhance the efficiency of photovoltaic panels and thermoelectric generators, as both are susceptible to performance degradation with temperature. Our investigation focuses on the integration of these materials with photovoltaic cells and thermoelectric generators, addressing critical challenges including thermal management, efficiency optimization, and operational stability.

1 Introduction

Radiative cooling (RC) offers promising solutions to reduce the significant electricity consumption of conventional cooling systems. This is particularly important as cooling is essential for socio-economic development and climate adaptation yet remains one of the most energy-intensive processes[1-5]. Furthermore, radiative cooling materials offer the potential for integration with other renewable energy technologies, such as photovoltaics and thermoelectric generators (TEGs). This integration allows for the strategic utilization of the passive net cooling effect they provide, thereby enhancing the overall efficiency and operational stability of these systems. In photovoltaic (PV) systems, high operating temperatures are detrimental to efficiency and lifespan. Monocrystalline silicon-based PV technologies typically operate at approximately 60 °C. This operational temperature not only shortens service lifetime but also results in performance degradation, which is quantified by the temperature coefficient, typically ≈0.5%/°C. Incorporating radiative cooling materials with additional capabilities such as UV and sub-bandgap reflection, along with light trapping, can effectively mitigate these thermal issues, leading to enhanced power output and efficiency[6]. Similarly, thermoelectric generators, which convert heat gradients into electrical energy, can benefit from radiative cooling by maintaining a lower cold-side temperature, thereby improving conversion efficiency[7]. We explore the strategic use of the net cooling effect resulting from radiative cooling materials integrated in PV cells and TEGs, enhanced by phase change heat exchangers. We predict and test the effects of reduced operating temperatures on output power enhancement and improved operational stability. These improvements could reduce dependency on active cooling systems and contribute to developing more robust, efficient, and sustainable energy solutions.

2 Results

2.1 PV performance enhanced by radiative cooling

We explore the capability of an all-photonic approach to enhance radiative cooling, UV and sub-bandgap reflection, and light trapping as a path to improve solar cells' efficiency. These ideal characteristics minimize heat gain due to inefficient light-electricity conversion while providing radiative cooling. We investigate a patterned surface of soda-lime glass, composed of hemispheres of 9 µm in diameter on top of a 75 µm layer and compare it to a compared to a flat counterpart of 79.5 µm. A numerical approach based on rigorous coupled-wave analysis (RCWA) and an electrical-thermal model was employed to assess the resulting improvements. Fig.1 shows the properties calculated by RCWA. It can be seen that the use of hemispheres clearly increases the emissivity beyond 8 µm, while enhancing light trapping in the useful part of the solar spectrum, thanks to the lower reflectivity due to the impedance matching. This is

---

[*] Corresponding author: juliana.jaramillo.fernandez@upc.edu

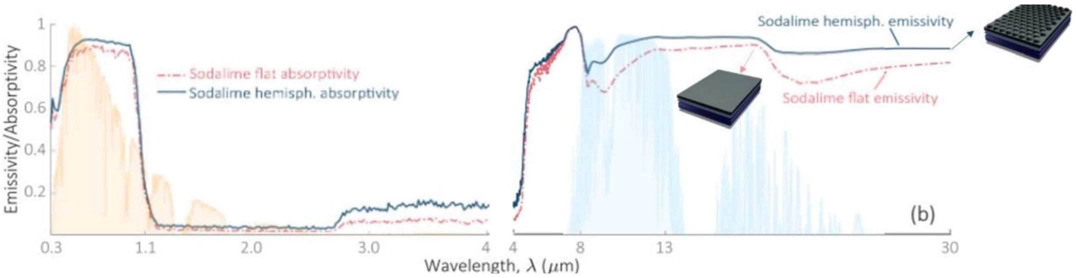

Fig 1. Unpolarized Hemispherical spectral emissivity of the soda-lime photonic structure, compared to a flat reference.

achieved without significantly decreasing UV and sub-bandgap reflection. To evaluate the improvement of solar cells' efficiency, we calculated the current-voltage characteristics (Fig.2a) and the maximum power generated by the cell[6] (Fig2b).

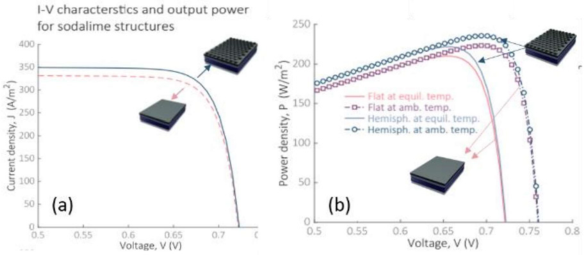

Fig. 2. Comparison between the soda-lime photonic structure and flat reference. a) Current-voltage characteristics and b) output power.

Using the numerical approach with the electrical-thermal model, it is estimated that soda-lime hemisphere photonic structures can improve the maximum power by 18.1% (Fig.2) and reduce the cell's temperature by 4°C compared to a glass-encapsulated solar cell[6]. We further study this approach on commercial solar cells.

2.2 TEGs energy production enhaced by radiative cooling

Thermoelectric generators are another application that can benefit from using RC materials. Heat pipes are often employed to maintain a lower cold-side temperature and enhance the efficiency of TEGs, because they preserve the key advantages of thermoelectricity, such as robustness, low maintenance, and the absence of moving parts. However, their thermal performance decreases under natural convection. To solve this challenge, we investigate a TEG that combines radiative cooling and phase-change heat pipes[7]. For this, we tested two thermoelectric generators with heat-pipes on their cold sides: one with a radiative coating and the other without it (Fig.3). The experimental tests show a reduction of the heat exchanger thermal resistance thanks to the radiative coating and consequently, an increase of electric production of 8.3 % with outdoor wind velocities of 1 m/s, and up to 54.8 % under free convection[7].

3 Conclusions

Overall, our results suggest that the incorporation of radiative cooling materials in both photovoltaics and thermoelectric generators could enhance their efficiency and operational stability. The integration of soda-lime glass with hemispherical patterns has demonstrated a significant improvement in the efficiency through the passive thermal management of solar cells. This effectively maximizes thermal radiation and light trapping across the solar spectrum while maintaining low reflectance in UV (0.3-0.375 μm) and sub-bandgap (1.1-4 μm) spectral regions. On the other hand, the observed improvements resulting from the radiative coatings on heat pipes suggest that they can ensure more stable and efficient energy generation, demonstrating significant potential for substantial gains in on-site applications. In summary, incorporating radiative cooling materials in both photovoltaics and thermoelectric generators shows promising potential to significantly enhance their efficiency, stability, and applicability in real-world energy systems.

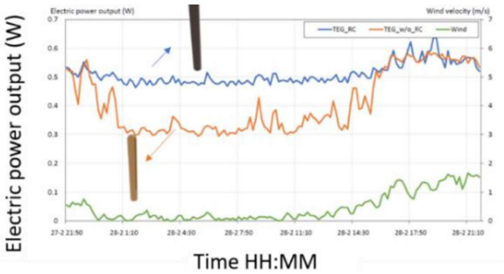

Fig 3. Electric power output from thermoelectric generators with heat pipes on their cold sides, comparing one with a radiative coating and one without, along with wind velocity.

References

1. J. Jaramillo-Fernandez, G. L. Whitworth, J. A. Pariente, A. Blanco, P. D. Garcia, C. Lopez, C. M. Sotomayor-Torres, Small, 15 (2019)
2. G. L. Whitworth, J. Jaramillo-Fernandez, J. A. Pariente, P. D. Garcia, A. Blanco, C. Lopez, C. M. Sotomayor-Torres, OPEX, 29 (2021)
3. Z. Ding, H. Li, X. Li, X. Fan, J. Jaramillo-Fernandez, L. Pattelli, J. Zhao, S. Niu, Y. Li, H. Xu, Adv. Mater. Interf. 11 (2024)
4. J. Jaramillo-Fernandez, H. Yang, L. Schertel, G. L. Whitworth, P. D. Garcia, S. Vignolini, C. M. Sotomayor-Torres, Adv. Sci. 9 (2022)
5. S. Fan & W. Li, NatPhot, 16 (2022).
6. G. Silva-Oelker, J. Jaramillo-Fernandez, OPEX. 30 (2022)
7. D. Astrain, J. Jaramillo-Fernandez, M. Araiz, A. Francone, L. Catalán, A. Jacobo-Martín, P. Alegria, C. M. Sotomayor-Torres, Appl. Therm. Eng. 225 (2023)