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Nighttime Radiative Cooling for Water Harvesting from Solar Panels

Wei Li, Minghao Dong, Lingling Fan, Jim Joseph John, Zhen Chen, and Shanhui Fan*

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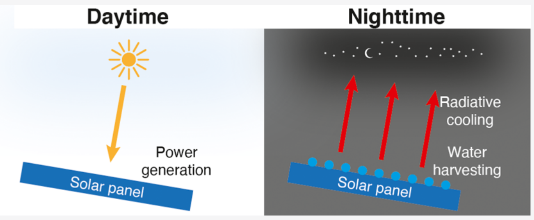

ABSTRACT: Photovoltaics has played a significant and increasingly important role in renewable energy harvesting. However, it only works during the daytime when the sun is accessible. In this paper, we propose to extend the functionality of solar panels into the nighttime for water harvesting, using nighttime radiative cooling. We first determine the suitable temperature and humidity range for nighttime water harvesting using solar panels and elucidate the water harvesting potential from solar panels. We further show that, through emissivity engineering, both the water generation rate and the suitable temperature and humidity range can be significantly improved. As a case study, we show that the average weekly water generation for solar panels in Dubai can reach 261 mL/m^2, sufficient for dust cleaning of solar panels. Moreover, it can be significantly enhanced up to 681 mL/m^2 with further emissivity engineering. The collected water can also be used for other applications including agrophotovoltaic and evaporative cooling of solar panels during the day, and can be extended to other solar energy harvesting systems. Our results point to new avenues to explore the nighttime utilization of a wide range of existing sky-facing solar energy harvesting systems and highlight the opportunities to use both the sun and outer space in existing energy systems.

KEYWORDS: *photovoltaics, radiative cooling, dew collection, water harvesting, self-cleaning*

The sun is the most important and easily accessible thermodynamic resource for human beings. Photovoltaics nowadays has played a significant and increasingly important role in renewable energy.[1,2] At the end of 2019, photovoltaics generation capacity amounted to 580 GW and continued to be the fastest-growing renewable technology.[1] However, due to the lack of the sun as a thermodynamic resource at night, photovoltaic systems, or in general any solar energy harvesting devices, which typically occupy large land areas, only work during the day and do not provide useful functionalities over a significant fraction of time.

On the other hand, at night there does exist a ubiquitous thermodynamic resource that has been largely underexplored: the low temperature of outer space at 3 K. Remarkably, the cold outer space can indeed be accessed through a process known as radiative cooling:[3−16] Any sky facing objects can emit a significant fraction of thermal radiation into outer space through the atmosphere transparent window in the mid-infrared wavelength range. With recent advances in nanophotonics and materials innovation, radiative cooling has become a frontier of renewable energy research,[7−14,17−19,15,16] and with possible applications including enhancing efficiencies of air conditioning[11,20] and solar energy systems,[21−28] thermal management,[19,29,30] and direct renewable power generation.[17,31−34] Moreover, using radiative cooling to reach below the dew point for water harvesting from the air has also been demonstrated as a promising clean water generation approach.[35−45] Due to its underlying mechanisms, radiative cooling works best in locations with good sky access. Interestingly, these coincide with locations where photovoltaic panels are typically installed. Therefore, it is of interest to explore the use of existing photovoltaic panels at night to perform radiative cooling. Such a process may enable a wide range of new functionalities for existing solar panels, which to date only work during the day.

In this paper, we propose to extend the functionality of solar panels into nighttime to perform water harvesting, using nighttime radiative cooling (Figure 1). Such a process, if possible, could serve as a cost-effective, sustainable, and widely applicable approach for immediate applications including dust cleaning on solar panels for reducing photovoltaic power loss[46] and agrophotovoltaics[47] by a synergistic combination of both photovoltaics and agriculture using the same area, as well as evaporative cooling of solar panel[48] during the day for reduced temperature and improved efficiency of solar panels. With theoretical analysis, we identified the suitable temperature and humidity range for nighttime water harvesting from solar panels, and we outlined the water harvesting potential under various conditions. We further show that, through photonic thermal emissivity engineering, both the amount of water production and the suitable temperature and humidity range can be significantly improved. As a case study, we show that in Dubai,

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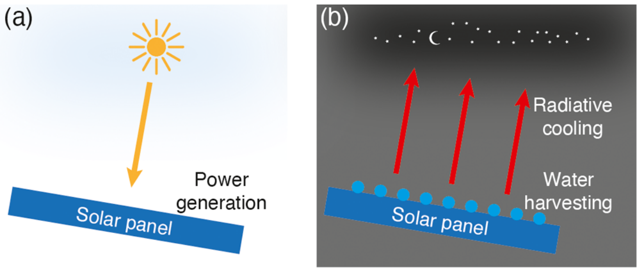

Figure 1. Solar panel for nighttime water harvesting. (a) Typical solar panels only work in the daytime with photovoltaic power generation. (b) Proposal of using solar panels at night for water harvesting from the air using radiative cooling.

the average weekly water generation from solar panels can reach 261 mL/m^2, sufficient for dust cleaning of solar panels. Moreover, this amount can be improved up to 681 mL/m^2, with careful engineering of spectral and angular emissivity characteristics on solar panels. Our results point to new avenues to explore the nighttime utilization of a wide range of existing sky-facing solar energy harvesting systems, which were thought to work only during the day, and highlight the opportunities to use both the sun and outer space as energy resources.[28]

RESULTS

We start our analysis by first identifying the suitable conditions for nighttime water harvesting using radiative cooling of solar panels. To enable water collection from a solar panel at night, a critical condition is to have the solar panel temperature T_{panel} reach below the dew point temperature $T_{dew\ point}$:

$$T_{panel} < T_{dew\ point} \tag{1}$$

The panel temperature T_{panel} can be determined by considering the heat balance in a nighttime radiative cooling process:

$$Q_{cool} = Q_{rad} - Q_{atm} - h(T_{ambient} - T_{panel}) \tag{2}$$

In eq 2, Q_{cool} is the net cooling power of the solar panel, which can be used to remove the latent heat from the condensation process. $Q_{rad} = \int d\Omega \cos\theta \int_0^\infty d\lambda\, I_{BB}(T, \lambda)\epsilon(\lambda, \theta)$ is the outgoing thermal radiation power from the panel. Here $\int d\Omega = 2\pi\int_0^{\pi/2} d\theta \sin\theta$ is the angular integral over a hemisphere. $I_{BB}(T, \lambda) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{hc/(\lambda k_B T)} - 1}$ is the spectral radiance of a blackbody at temperature T, where h is Planck's constant, k_B is the Boltzmann constant, c is the speed of light, and λ is the wavelength. $\epsilon(\lambda, \theta)$is the solar panel emissivity spectrum, taken from ref 24 and shown in Figure 4d. $Q_{atm} = \int d\Omega \cos\theta \int_0^\infty d\lambda\, I_{BB}(T_{amb}, \lambda)\epsilon(\lambda, \theta)\epsilon_{atm}(\lambda, \theta)$ is the downward atmospheric thermal radiation absorbed by the panel. The angle-dependent emissivity of the atmosphere is given by $\epsilon_{atm}(\lambda, \theta) = 1 - t(\lambda)^{1/\cos\theta}$ where $t(\lambda)$ is the atmospheric transmittance in the zenith direction. h = 8 W·m^{-2}·K^{-1} is the nonradiative heat transfer coefficient between the panel and the environment.

At this point, to find out the lowest possible temperature a solar panel can reach, we set Q_{cool} as zero and compute eq 2. We will later on take the condensation process into account when we compute the amount of water generation. It should be noted that, the atmospheric transmittance $t(\lambda)$ is strongly dependent on ambient temperature $T_{ambient}$ and relative humidity (RH).[49] Therefore, for a given solar panel with fixed emissivity, the lowest cooling temperature of the solar panel T_{panel} is a function of $T_{ambient}$ and RH. This correlation is shown in Figure 2a, where the achievable nighttime radiative cooling temperature reduc-

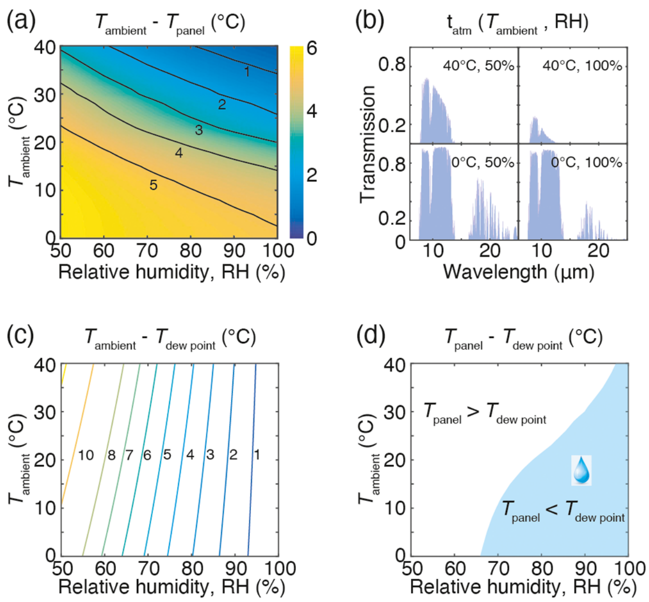

Figure 2. Identification of suitable temperature and relative humidity ranges for water harvesting from solar panels. (a) Without considering water condensation, achievable nighttime radiative cooling temperature reduction ($T_{ambient} - T_{panel}$) as functions of ambient temperature $T_{ambient}$ and relative humidity RH. This correlation origins from the atmosphere transmission spectra t_{atm} dependency on ambient temperature $T_{ambient}$ and relative humidity RH. (b) Ambient temperature $T_{ambient}$ and relative humidity RH dependent atmosphere transmission spectra $t_{atm}(T_{ambient}, \text{RH})$. t_{atm} decreases with increased $T_{ambient}$ and RH. (c) Temperature difference between dew point and ambient temperature ($T_{ambient} - T_{dew\ point}$), as functions of ambient temperature and relative humidity. (d) Water harvesting is possible, when the panel temperature is lower than the dew point. The suitable range of temperature and humidity is plotted in the blue shaded area, by comparing parts a and c.

tion ($T_{ambient} - T_{panel}$) from a solar panel is shown as functions of $T_{ambient}$ and RH. In general, lower $T_{ambient}$ and RH will lead to better cooling performance, due to more transparent atmosphere conditions (Figure 2b).

On the other hand, the dew point temperature $T_{dew\ point}$ is also a function of ambient temperature $T_{ambient}$ and relative humidity RH:[50]

$$T_{dewpoint} = \frac{243.12 \times \left[\ln(\text{RH}) + \frac{17.62 \times T_{ambient}}{243.12 + T_{ambient}}\right]}{17.62 - \left[\ln(\text{RH}) + \frac{17.62 \times T_{ambient}}{243.12 + T_{ambient}}\right]} \tag{3}$$

As shown in Figure 2c, the temperature difference between the dew point and the ambient temperature ($T_{ambient} - T_{dew\ point}$) is strongly dependent on RH and $T_{ambient}$. By comparing parts a and c of Figure 2, one can find out the regime where eq 1 is satisfied and water harvesting is possible, as highlighted in the light blue shaded regime in Figure 2d. This regime can be understood as a trade-off: a condition of lower $T_{ambient}$ and RH (lower water content in the air and more transparent atmosphere) provides better radiative cooling performance, but meanwhile such a condition also corresponds to a lower dew point temperature $T_{dew\ point}$, which makes it harder for water harvesting. As a result of such trade off, for

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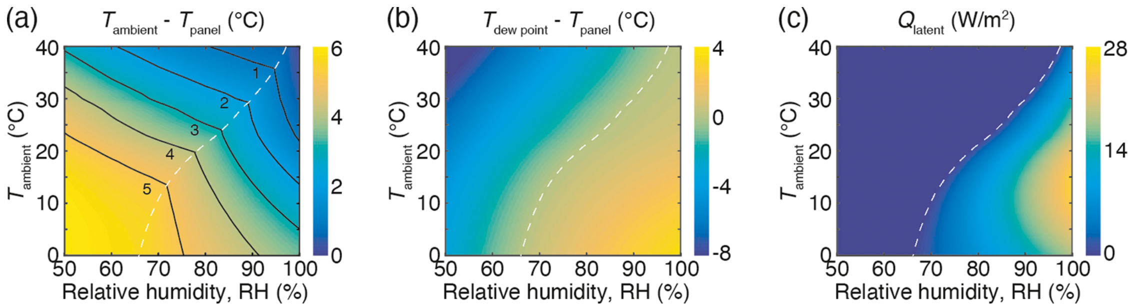

Figure 3. With considering dew condensation, analysis of temperature and water condensation latent heat from a solar panel. (a) With considering water condensation, temperature reduction ($T_{ambient} - T_{panel}$) as functions of ambient temperature $T_{ambient}$ and relative humidity RH. The white dashed line indicates the boundary of the condensation and noncondensation regimes. As compared to Figure 2a, panel temperature remains unchanged within the noncondensation regime but gets elevated within the condensation regime, due to the latent heat. (b) Comparison between dew point $T_{dew\ point}$ and panel temperature T_{panel}: within the condensation regime, $T_{panel} < T_{dew\ point}$, within the noncondensation regime, $T_{panel} > T_{dew\ point}$. (c) Latent heat released by the condensation process Q_{latent} as functions of ambient temperature and relative humidity.

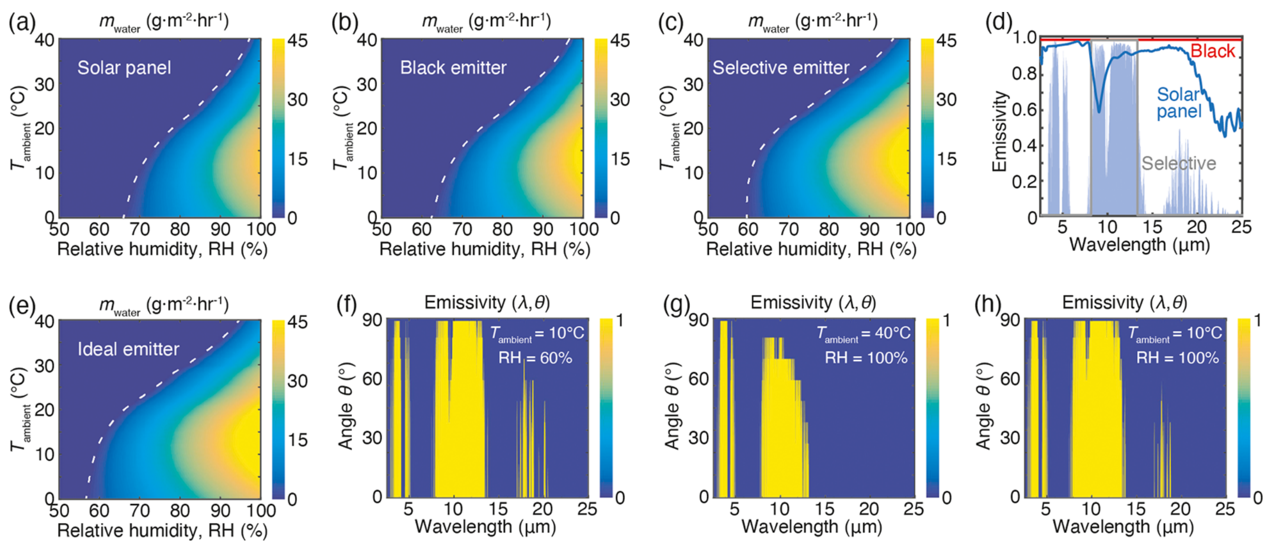

Figure 4. Water generation rate from a solar panel using radiative cooling and its improvement using emissivity engineering. (a) Calculated water generation rate from a solar panel, as functions of ambient temperature and relative humidity. (b) Calculated water generation rate from a black emitter, as functions of ambient temperature and relative humidity. (c) Calculated water generation rate from a wavelength selective emitter, as functions of ambient temperature and relative humidity. (d) Emissivity spectra of a solar panel (blue), a blackbody emitter (red), and an ideal selective emitter (gray). The blue shaded area is the atmosphere transmission spectrum for reference. (e) Calculated water generation rate from an ideal spectral–angular–selective emitter, as functions of ambient temperature and relative humidity. Three exemplary spectral–angular–selective emissivity profiles under different ambient temperatures and relative humidities are shown in parts f–h. Both the water generation rate and the suitable temperature and humidity range (outlined by the white dashed curve in parts a, b, c, and e) can be improved through emissivity engineering.

efficient water harvesting it is in fact more preferable to operate in a regime where the relative humidity is high. For example, for a solar panel at an ambient temperature $T_{ambient}$ = 10 °C, a relative humidity RH > 69.6% is required to trigger the condensation process.

We now take the condensation process into account by considering the net cooling power of the solar panel Q_{cool} and use it to balance the latent heat from the condensation process Q_{latent}: $Q_{cool} = Q_{latent}$. In the condensation process, Q_{latent} can be determined from[44]

$$Q_{latent} = (\text{Le})^n \frac{h}{\gamma} [\text{RH} \times P_{H_2O}(T_{ambient}) - P_{H_2O}(T_{panel})] \tag{4}$$

where Le is the Lewis number and n is a parameter depending on the convection condition and configuration of the solar panel. Based on ref 44, we choose $Le = 0.87$, $n = -2/3$, $(Le)^n = 1.1$ for a flat inclined plate. γ is the psychrometer constant (67 PaK^{-1} at 20 °C), P_{H_2O} is the saturation vapor pressure, depending only on temperature. h is the convective heat transfer coefficient as was also used in eq 2.

By solving eqs 2 and 4, we obtain Q_{latent} and T_{panel}. As shown in Figure 3a, outside the condensation regime, the cooling temperature reduction ($T_{ambient} - T_{panel}$) remains the same as Figure 2a. However, within the condensation regime, the latent heat released by the condensation process will in turn elevate the panel temperature and lead to a reduced temperature reduction. By directly comparing T_{panel} and $T_{dew\ point}$, it is further shown that within the condensation regime, T_{panel} remains smaller than $T_{dew\ point}$ (Figure 3b). A higher RH and lower $T_{ambient}$ give a larger temperature difference between $T_{dew\ point}$ and T_{panel}. However, as shown in Figure 3c, the maximum point of Q_{latent} in the condensation does not overlap with the maximum temperature difference between $T_{dew\ point}$ and T_{panel}. This is a trade-off between the cooling temperature reduction and the

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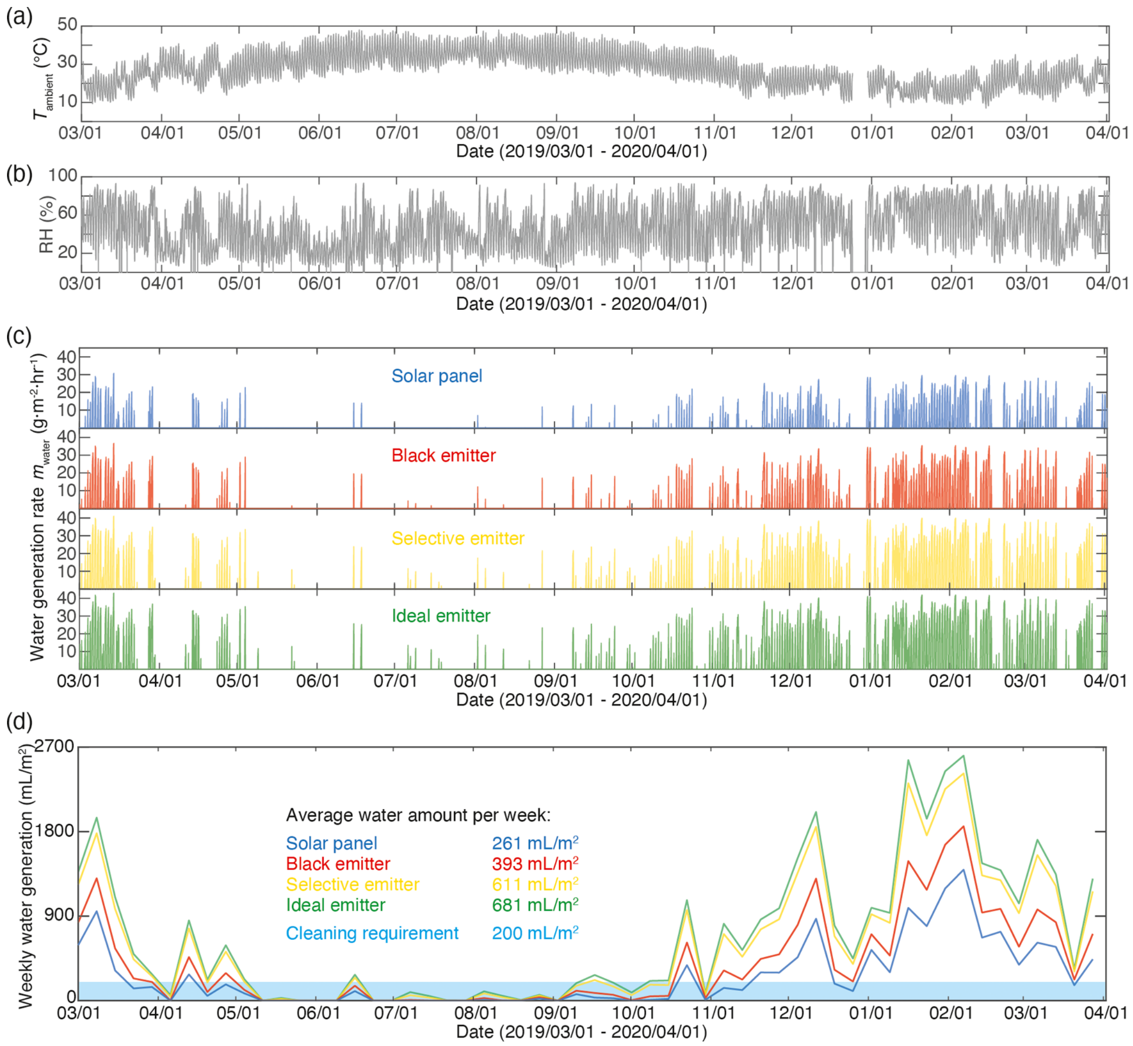

Figure 5. Case study for evaluation of year-round water generation performance from solar panels in MBR Solar Park, Dubai,[53] and its improvement using emissivity engineering. (a) Year-round ambient temperature in Dubai. (b) Year-round relative humidity in Dubai. (c) Year-round hourly water generation rate in Dubai, from a standard solar panel (blue), a blackbody emitter (red), a spectral selective emitter (yellow), and an ideal spectral-angular-selective emitter (green). (d) Year-round weekly water generation rate of a solar panel (blue), a blackbody emitter (red), a spectral selective emitter (yellow), and an ideal spectral-angular-selective emitter (green). The minimum water amount requirement for weekly cleaning is 200 mL/m^2, as indicated by the light blue shaded area. The average water generation per week for a solar panel, a blackbody emitter, a spectral selective emitter, and an ideal spectral-angular-selective emitter are 261 mL/m^2, 393 mL/m^2, 611 mL/m^2, 681 mL/m^2, respectively.

actual water content in the air that are dependent on RH and $T_{ambient}$.

The latent heat from the condensation process Q_{latent} (Figure 3c) can be directly used to determine the generation rate m'' of water harvesting:

$$m'' = \frac{Q_{latent}}{\Delta} \tag{5}$$

where Δ is the latent heat per unit mass of water. Figure 4a highlights the generation rate of water harvesting from a solar panel, as a function of $T_{ambient}$ and RH. The suitable regime of condensation, outlined as the white dashed curve in Figure 4a, is consistent with Figure 2d. The maximum water generation rate obtained from a solar panel is 40.2 g·m^{-2}·h^{-1} (12 °C, 100%).

All the calculations above assume an emissivity spectrum of the solar panel shown as the blue curve in Figure 4d. Recent advances of nanophotonic controlled thermal radiation[51] provide powerful tools to engineer the emissivity profiles at will. This opens up possibilities to further improve radiative cooling and water harvesting performances. Here we present a set of emissivity profiles and their impact on water harvesting (Figure 4b−h). First, a black emitter in the infrared spectrum (Figure 4d, red curve) can be used to improve both the water generation rate and suitable temperature and humidity range (Figure 4b). The maximum water generation rate can be improved from 40.2 g·m^{-2}·h^{-1} (12 °C, 100%) to 46.4 g·m^{-2}·h^{-1} (15 °C, 100%). At the condition of $T_{ambient}$ = 10 °C, RH = 70%, the water generation rate can be improved from 0.52 g·m^{-2}·h^{-1} to 5.54 g·m^{-2}·h^{-1}. When $T_{ambient}$ = 10 °C, the minimum RH to trigger the condensation process is reduced from 69.6% to 66%. Second, a selective emitter with unity emissivity at 8−13 μm and zero emissivity elsewhere (Figure 4d, gray curve) can be used to further improve the performance (Figure 4c). The maximum rate can be improved to 49.4 g·m^{-2}·h^{-1} (15 °C, 100%). At the condition of $T_{ambient}$ = 10 °C, RH = 70%, the water generation rate can be improved to 12.3 g·m^{-2}·h^{-1}. When $T_{ambient}$ = 10 °C, the minimum RH to trigger the condensation process is reduced to 60.6%.

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Since the magnitude, spectral position, and angle dependency of the atmosphere transmission are all strongly dependent on the ambient temperature and humidity (Figure 2b), a selective emitter as presented in parts c and d of Figure 4 does not necessarily represent the most ideal emitter for radiative cooling and water harvesting purpose. Therefore, it is of interest to explore the ideal emissivity profiles at various conditions and their associated impact on water harvesting. This can be achieved by performing optimization[52] when self-consistently computing eqs 2 and 4. Here we optimize the spectral-angular-dependent emissivity $\epsilon(\lambda, \theta)$ by comparing Q_{rad} and Q_{atm} at each spectral and angular channel (λ, θ), at a given T_{panel}. The emissivity at each channel $\epsilon(\lambda, \theta)$ is set to 1, if the outgoing radiation power is larger than the atmosphere downward radiation absorbed by the panel. The emissivities at the rest of the channels are set to zero. In doing so, the water harvesting performance can be further improved (Figure 4e), with a carefully designed thermal emissivity profile at each temperature and relative humidity condition (Figure 4f–h). As shown in Figure 4e, the maximum mass flux can be improved to 51.3 $g \cdot m^{-2} \cdot h^{-1}$ (15 °C, 100%). At the condition of $T_{ambient}$ = 10 °C, RH = 70%, the mass flux of water harvesting can be improved to 14.3 $g \cdot m^{-2} \cdot h^{-1}$. When $T_{ambient}$ = 10 °C, the minimum RH to trigger the condensation process is reduced to 59%. Therefore, with a carefully designed thermal emissivity profile, one can enable water harvesting in a regime (for example $T_{ambient}$ = 10 °C, RH = 60%) that can not be accessed with standard solar panel, black emitter or even 8−13 μm selective emitter, which has been widely considered as the near-ideal emitter in radiative cooling.[9]

We now discuss the significance of the water generation capability using radiative cooling from solar panels. One of the immediate applications is to use the generated water for dust cleaning on solar panels. Dust accumulation on solar panels has been an important power loss factor in photovoltaics.[46] Using the water generated from solar panels can potentially provide a cost-effective, self-sustainable, and widely applicable approach for dust cleaning. As a case study, we take the year-round temperature (Figure 5a) and relative humidity (Figure 5b) data from MBR Solar Park in Dubai, one of the world's largest single-site solar parks,[53] and compute the year-round water generation rates from solar panels, blackbody emitter, 8−13 μm selective emitter, and the ideal spectral-angular-selective emitter, based on the results outlined in Figure 4. To illustrate the full potential, we assume clear sky nights and ignore the effects of cloud coverage in the calculation. The hourly generation rate and weekly water generation rate are illustrated in parts c and d of Figure 5, respectively. For a standard solar panel, water generation happens in most of the days from October to April when the ambient temperature is low and relative humidity is high. From May to September, water generation is less accessible due to the high ambient temperature and low relative humidity. The average weekly water generation for solar panels is 261 mL/m^2. As a reference, 200 mL/m^2 is the minimum requirement for weekly cleaning in solar farms that typically use tractor mounted brush cleaning systems.[53] This result indicates that with a proper water collection scheme, the amount of water generation by radiative cooling from a solar panel can fulfill the requirement for solar panel cleaning purposes. More encouragingly, with emissivity engineering, not only the water generation rate but also the days when water generation is possible can be significantly improved (Figure 5c). As a result, the average weekly water generation for blackbody emitter, 8−13 μm selective emitter, and the ideal spectral-angular-selective emitter can reach 393 mL/m^2, 611 mL/m^2, and 681 mL/m^2, respectively (Figure 5d). These results highlight the significant potential of using radiative cooling and photonic emissivity engineering for water harvesting and self-cleaning of solar panels.

■ DISCUSSION

We briefly comment on a few practical considerations toward implementing this technique as well as a few other potential applications. First, as discussed above, using a blackbody emitter, a 8−13 μm selective emitter, and the ideal spectral-angular-selective emitter can significantly enhance the water generation capability of solar panels. To maintain the daytime power generation performance of solar panels, this would require engineering the solar panel emissivity profile in the infrared spectrum without sacrificing the high transmission in the solar spectrum that is above the bandgap of the solar cells. Such a spectral feature can be achieved with recently proposed micropatterned structures[23] or multilayer films.[24] Furthermore, the heating of a solar cell has significant adverse consequences on both its efficiency and its reliability.[54] Such a spectral feature has the potential to reduce the daytime solar panel operating temperature by over 8 °C and enhance the solar panel absolute efficiencies by 1%.[24] Therefore, it can be beneficial for both nighttime water harvesting and daytime solar cell efficiency enhancement. Second, due to the seasonal variation of water generation rates (Figure 5, parts c and d), to enable regular weekly cleaning, it would be beneficial to have a proper water collection system to use the excess water generated in humid seasons for dry seasons. This could be achieved with collection tubes at lower edges of the solar panels. Third, although we choose the data from Dubai as a case study, this technique is widely applicable to any regions with similar or more favorable environment conditions,[55,56] i.e., lower temperatures and higher humidity.

Comparing with other ambient water harvesting techniques[57] such as sorption-based water harvesting[58] and thermoelectric condensers,[59] our proposed technique is passive, and can be naturally integrated with solar panel as a retrofit, without increasing the system complexity. The solar panels are typically installed in places where radiative cooling processes are most effective. Moreover, other water harvesting techniques need to be on the backside of the solar panel to avoid degrading of daytime photovoltaic performance. On the contrary, the radiative cooling layer is on the front side of the solar panel. It can be designed to maintain or even enhance daytime photovoltaic performance.[24] For regions where more water generation is demanded or the temperature and humidity are not sufficient for radiative cooling-based water generation, our technique can be combined with other water harvesting techniques. For example, a solar panel performs radiative cooling-based water harvesting on the front side and thermoelectric-based cooling on the back side.

Finally, in addition to dusting cleaning applications, the collected water can also be used for a wide range of applications such as agrophotovoltaics,[46] where photovoltaics and agriculture are synergistically combined using the same area, as well as evaporative cooling of solar panels[48] during the day for reduced temperature and improved efficiency of solar panels. More broadly, it would be of interest to explore nighttime radiative cooling from solar panel for other nighttime operations as well, such as nighttime power generation[17,31] and nonevaporative cooling of water.[11]

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In summary, we have proposed to use radiative cooling from solar panels for nighttime water harvesting applications. With a comprehensive analysis, we identify the ambient temperature and relative humidity regime that are suitable for solar panel water harvesting and outline the water harvesting potential from this approach. We further show that both the water generation rate and the suitable regime can be significantly improved, with careful photonic engineering of thermal emissivity using black emitter, selective emitter and spectral-angular-selective emitter. The collected water can also be used for other applications including agrophotovoltaics and evaporative cooling of solar panels during the day and can be extended to other solar energy harvesting systems. Broadly, our results point to new avenues to explore the nighttime utilization of a wide range of existing naturally sky-facing solar energy harvesting systems, which were thought to work only during the day. Our results highlight the opportunities to use both the sun and outer space as energy resources.

AUTHOR INFORMATION

Corresponding Author

Shanhui Fan − *Department of Electrical Engineering, Ginzton Laboratory, Stanford University, Stanford, California 94305, United States;* orcid.org/0000-0002-0081-9732; Email: shanhui@stanford.edu

Authors

Wei Li − *Department of Electrical Engineering, Ginzton Laboratory, Stanford University, Stanford, California 94305, United States;* orcid.org/0000-0002-2227-9431

Minghao Dong − *Jiangsu Key Laboratory for Design & Manufacture or Micro/Nano Biomedical Instruments, School of Mechanical Engineering, Southeast University, Nanjing 210096, P. R. China*

Lingling Fan − *Department of Electrical Engineering, Ginzton Laboratory, Stanford University, Stanford, California 94305, United States*

Jim Joseph John − *Dubai Electricity & Water Authority, 564 Dubai, UAE*

Zhen Chen − *Jiangsu Key Laboratory for Design & Manufacture or Micro/Nano Biomedical Instruments, School of Mechanical Engineering, Southeast University, Nanjing 210096, P. R. China;* orcid.org/0000-0002-5422-8807

Complete contact information is available at:
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Notes

The authors declare no competing financial interest.

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