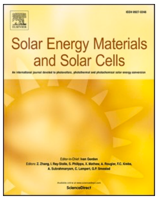
Solar Energy Materials & Solar Cells 228 (2021) 111136

Contents lists available at ScienceDirect

Solar Energy Materials and Solar Cells

journal homepage: http://www.elsevier.com/locate/solmat



Is it possible for a photovoltaic-thermoelectric device to generate electricity at night?

Bin Zhao [a], Mingke Hu [b], Xianze Ao [a], Qingdong Xuan [c], Zhiying Song [a], Gang Pei [a,*]

[a] *Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Hefei, 230027, China*
[b] *Department of Architecture and Built Environment, University of Nottingham, University Park, Nottingham, NG7 2RD, UK*
[c] *School of Automotive and Transportation Engineering, Hefei University of Technology, 193 Tunxi Road, Hefei, 230009, China*

ARTICLE INFO

Keywords:
Radiative cooling
Thermoelectric generator
Nighttime power generation
PV-TE

ABSTRACT

Photovoltaic-thermoelectric (PV-TE) conversion is a promising method for power generation, which converts solar power into electricity using the photovoltaic (PV) effect of solar cells and simultaneously generates electricity by the Seebeck effect of the thermoelectric (TE) device based on the waste heat of solar cells. Here, the power generation of the PV-TE device at night is experimentally demonstrated using radiative cooling that harnesses the cold of the universe directly. The PV-TE device is constructed by attaching a TE device on the bottom of the glass-covered PV module, with a heat sink stuck on the opposite side of the TE device. The open-circuit voltage of the TE device integrated into the PV-TE device was measured to be approximately 9 mV, indicating that the PV-TE device can definitely generate electricity from the darkness. Moreover, a new configuration of the PV-TE device for continuous power generation in the day and night is conceptually proposed for further consideration. In summary, this work proves the possibility of the PV-TE device for nighttime power generation, which could provide an alternative pathway for a wide range of nighttime and all-day power-consumed applications, such as lower power sensors and monitors.

1. Introduction

Exploring efficient and clean methods for power generation is a meaningful project since the massive use of fossil fuel for power generation has already brought serious environmental problems, such as the greenhouse effect. Photovoltaic (PV) conversion is exactly one of the clean methods for power generation [1], which converts solar photons with high energy levels into electricity directly. Besides, thermoelectric (TE) conversion can also generate electricity using a clean way by converting heat energy into electricity directly based on the Seebeck effect of the TE generator [2]. Currently, many researchers have focused on the topic of photovoltaic-thermoelectric (PV-TE) hybrid conversion by integrating PV and TE effect into a single device [3–5]. PV-TE conversion is a promising power generation method that converts solar photons into electricity via the PV effect of solar cells and simultaneously generates electricity using the TE effect based on the waste heat of solar cells, which improves the efficiency of the power generation.

There are numerous previously reported works on the topic of the PV-TE hybrid conversion ranging from materials sciences to engineering applications. Sark [6] conducted a performance analysis of PV-TE hybrid modules by attaching TE generators to the back of the PV modules directly and numerically revealed that the total power generation efficiency can be improved by 8–23%. Li et al. [7,8] integrated PV modules and TE generator using a flat plate micro-channel pipe that exhibits high thermal transfer performance. The experiment demonstration was conducted in the laboratory using a solar simulator and water-cooling method and the results showed that the electrical efficiency of the hybrid module is higher than that of the stand-alone PV module, indicating the feasibility of the PV-TE conversion. Kossyvakis et al. [9] experimentally tested the performance of a tandem PV–TE device based on the polycrystalline silicon solar cells and dye-sensitized solar cells, which showed that the efficiency of the PV-TE device when the TE generator with shorter thermoelements is highest. Moreover, the PV-TE device can be further extended for solar concentration [10] and solar splitting [11] conditions, such as using the additional reflective mirror for solar concentration and spectrally selective coating for solar splitting.

It is definitely that the PV-TE device works well in the daytime for power generation to supply the loads, such as lighting. However, is it possible for the PV-TE device to generate electricity at night, and how?

---

* Corresponding author.
E-mail address: peigang@ustc.edu.cn (G. Pei).

https://doi.org/10.1016/j.solmat.2021.111136
Received 21 December 2020; Received in revised form 4 February 2021; Accepted 17 April 2021

Interestingly, electricity can be generated by the TE device at night uniquely using the cold universe (~3K) and the warm ambient environment as the heat sink and heat source of the device, respectively. Raman et al. [12] experimentally obtained the light from the darkness using a radiative cooling based TE device where a thermal emitter was attached on the top of the TE device and exposed to the clear sky. The sky-faced emitter was cooled below the temperature of the opposite side of the TE device passively by radiative cooling. Thus, a temperature difference occurs, corresponding to the electricity generation. Here, radiative cooling is a passive cooling technique that can achieve a sub-ambient cooling phenomenon by radiating the heat into the cold universe via the transparent atmospheric window (i.e., 8–13 μm) [13–16]. In recent years, radiative cooling based TE device has aroused many interests [17–22]. Mu et al. [17] integrated a multilayer film to TEG for all-day power generation and a maximum output voltage of 0.5 mV and an all-day average voltage of 0.18 mV were obtained. Ishii et al. [18] constructed a radiative cooling TE device for all-day continuous power generation by adding a solar reflective emitter on the top of the TE device. Outdoor testing results showed that the proposed device can generate voltage in the day and night continuously without dropping to zero. Also, the maximum temperature difference of the TE device was predicted to be nearly 5 °C. To further improve the performance of the radiative cooling based TE device, Fan et al. [19] made a systematic optimization of the device from the aspects of spectral properties of the emitter, thermal convection, and the TE device's figure of merit. Zhao et al. [20] also presented the modeling and optimization of the radiative cooling based TE device and the maximum power point of the device was found to be different from the results previously reported. Based on the above review, if we applied the radiative cooling method to the PV-TE device at nighttime, it is possible that the PV-TE device can generate power from the darkness and this will be a new branch for research of PV-TE hybrid utilization. More importantly, compared with the traditional PV-TE utilization that only uses solar energy and all-day radiative cooling based TEG utilization that only uses the cold universe, it is thermodynamically reasonable and advantageous for PV-TE device to respectively use solar energy at daytime and the cold universe at nighttime and this is also what we do in this paper. Specifically, solar irradiance is generally an order of magnitude greater than the radiative cooling power, so harvesting solar energy for power generation during daytime is the better choice, especially for PV conversion since the exergy efficiency of solar PV conversion is dramatically higher than that of solar thermal conversion. Furthermore, harnesses the cold of the universe is the better choice at night when the sunlight disappears and this provides a new way to generate electricity from the darkness.

In this work, we experimentally demonstrate that the PV-TE device can generate voltage at nighttime. The PV-TE device is constructed by attaching a TE device to the bottom of the PV module and the PV module is covered with transparent glass. Then, the optical property of the PV module that is exposed to the sky directly is characterized and analyzed. Next, outdoor testing is conducted by measuring the voltage output of the TE device and PV module in the day and night, respectively. Finally, a new configuration of the PV-TE device for continuous power generation in the day and night is proposed for deep consideration.

2. Description of the experimental set-up

2.1. Concept description

The schematic of the PV-TE device for all-day power generation is presented in Fig. 1. In the daytime, the PV module absorbs solar photons and partly converts them to electricity, while the remaining absorbed solar power is dissipated into heat and can be further used to generate electricity by the TE device using the Seebeck effect. In the nighttime, the temperature of the PV module drops to be lower than the temperature of the ground-faced side of the TE device due to the existence of radiative cooling. Thus, the heat is extracted from the ambient environment by convection and conduction heat transfer to the bottom of the TE device and finally pumped to the cold universe using radiative cooling, with electricity output generated by the TE device.

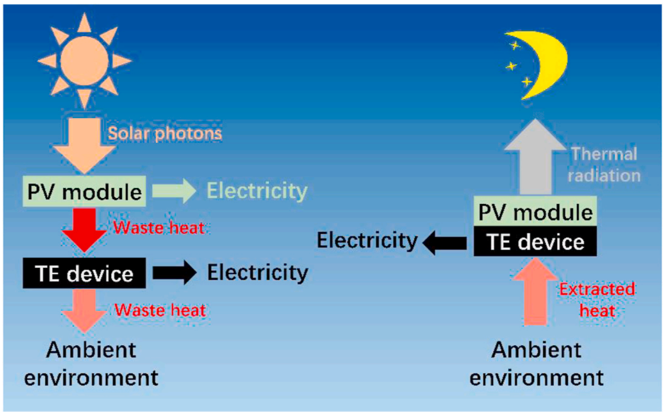


Fig. 1. Concept of the PV–TE device for power generation.

2.2. Description of the PV–TE device and experimental set-up

The PV-TE device, as shown in Fig. 2(a), is constructed by attaching a commercial TE device (TEG1-127-1.4-1.0) to the bottom of the PV module. To enhance the heat transfer process at the bottom surface of the TE device, a heat sink is fixed on the bottom surface of the TE device. All contact surfaces are connected using the thermal conductive glue (HY510, Halnziye). The PV module is fabricated by laminating a monocrystalline silicon solar cell on the 3.2-mm-thick glass with white Tedlar film and ethylene-vinyl-acetate film as the backplate and adhere layer, respectively. As shown in Fig. 2, the PV-TE device is held by a planar thermal insulation plate equipped with an aperture in the center. Besides, the TE device with the heat sink is placed in the aperture of the thermal insulation plate, thus the bottom side of the TE device is free to contact with the ambient air. The reflective layer on the top of the thermal insulation plate is used to reflective the solar irradiance and decrease its effect on the voltage output.

During testing, the experimental set-up was set on the rooftop of a building in the University of Science and Technology of China at Hefei (117°E, 32°N), China. A T-type thermocouple is fixed on the bottom surface of the PV module to monitor the module's temperature and the ambient temperature is also measured using a T-type thermocouple fixed in a shelter to avoid the sunshine. Besides, the solar irradiance is measured using the pyranometer (TBQ-2, Jinzhou Sunshine Technology Co.Ltd). All data are recorded by a data logger (LR8402-21, HIOKI). Moreover, the open-circuit voltage values of the PV module and the TE device are measured using the data logger directly.

2.3. Optical characterization of the PV module

In the nighttime, the PV module is exposed to the clear sky and responsible for radiative cooling to drive the power generation of the PV-TE device, as shown in Fig. 1. According to the conclusions reported in previously published papers [23–26], the ideal spectral requirement of the thermal emitter for efficient radiative cooling is that the thermal emitter needs to have a high thermal emissivity in the atmospheric window or the whole mid-infrared wavelength band. Here, the spectral reflectivity of the PV module is measured using the Fourier Transform Infrared Spectrometer (Nicolet iS10, Thermo Scientific) with an integrating sphere (Mid-IR IntegratIR, Pike Technologies). The spectral emissivity of the PV module is then calculated using the energy balance and Kirchhoff's law. It is clear from Fig. 3 that the PV module exhibits high emissivity in the whole mid-infrared wavelength band with an averaged emissivity of approximately 0.9, illustrating that the PV

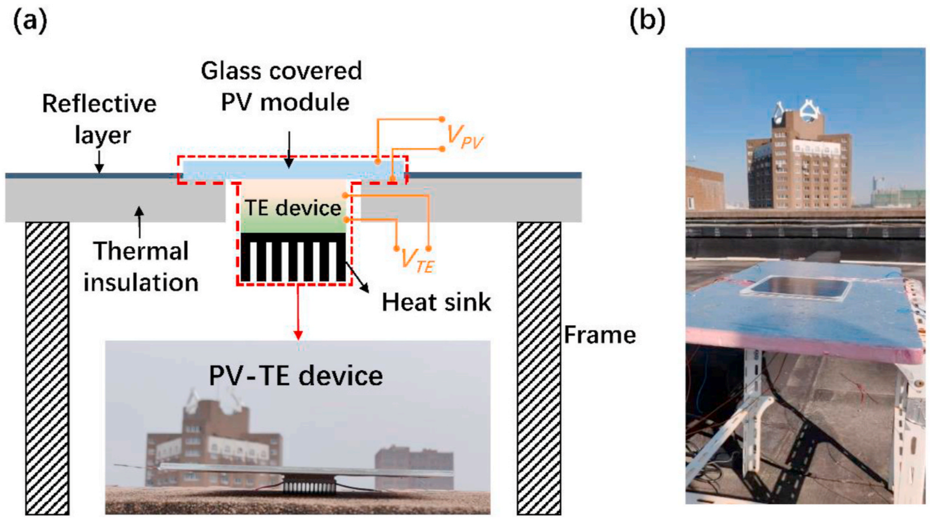


Fig. 2. Schematic of the PV−TE module and experimental set-up.

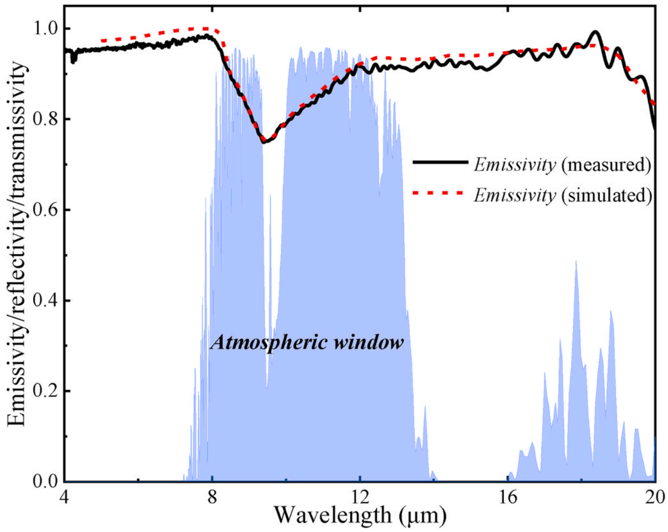


Fig. 3. Measured emissivity (black curve) of the PV module. Simulated emissivity (red curve) of a 3.2-mm-thick soda-lime glass and transmissivity of the atmospheric under a typical condition are presented as references. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

module is a good candidate for radiative cooling. Besides, the spectral emissivity of a 3.2-mm-thick soda-lime glass is simulated using the classical transfer matrix method, which shows that the emissivity of the soda-lime glass is consistent with that of the PV module, indicating that the high emissivity of the PV module is entirely contributed by the thick glass cover. The optical constant of the soda-lime glass is extracted from the previous work [27]. It is noted that the reason for emissivity drop at the wavelength of nearly 9 μm is that there is an optical mismatch at the air/glass interface, but it can be perfectly modified using the patterned surfaces (e.g., micro pyramid structures [28] and gratings [16,29]) and these methods have already been reported.

3. Results and discussions

3.1. Testing condition

The experimental testing was continuously conducted for 48 h from 24 October 2020 to 25 October 2020. The measured ambient temperature, PV module temperature, and solar irradiance are presented in Fig. 4. It is found that the condition of solar irradiance on 24 October 2020 is better than that on 25 October 2020 since the fluctuation of the solar irradiance curve of the former is obviously smaller than that of the latter. Also, ambient temperature changes slowly and varies within a range of approximately 10 °C–20 °C. Moreover, the temperature of the PV module changes rigorously with the change of solar irradiance. In the daytime, the temperature of the PV module is higher than the ambient temperature with a maximum and an average temperature of approximately 20 °C and 9 °C, respectively. In the nighttime, the temperature of the PV module is lower than the ambient temperature due to the existence of radiative cooling. The maximum and average temperature difference between the PV module and ambient air is recorded to be nearly 7.0 °C and 5.3 °C in the clear sky condition.

3.2. Power generation of the PV-TE device

The open-circuit voltage of the PV module and the TE device integrated into the PV-TE device were measured and presented in Fig. 5. It is noted that the voltage curve inserted in Fig. 5(a) was measured on 24 October 2020 when the sky is mostly sunny. The measured voltage almost shows a stepped change within the voltage range of nearly 0–0.6 V. Specifically, the open-circuit voltage of the PV module is approximately 0.6 V in the daytime and drops to 0 V in the nighttime, which indicates that the PV module works well in the daytime.

Fig. 5(b) describes the open-circuit voltage of the TE device in the

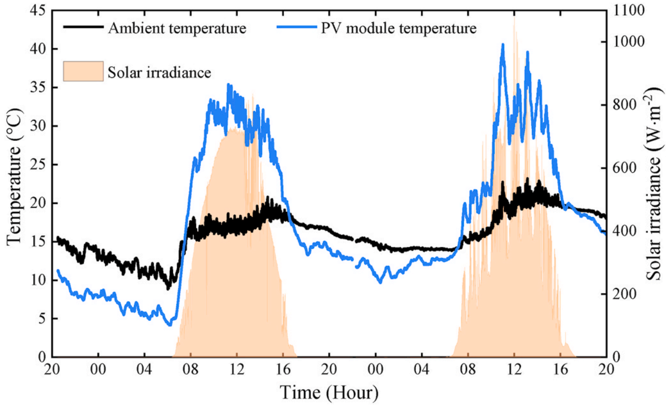


Fig. 4. Measured ambient temperature, PV module temperature, and solar irradiance power during the testing period.

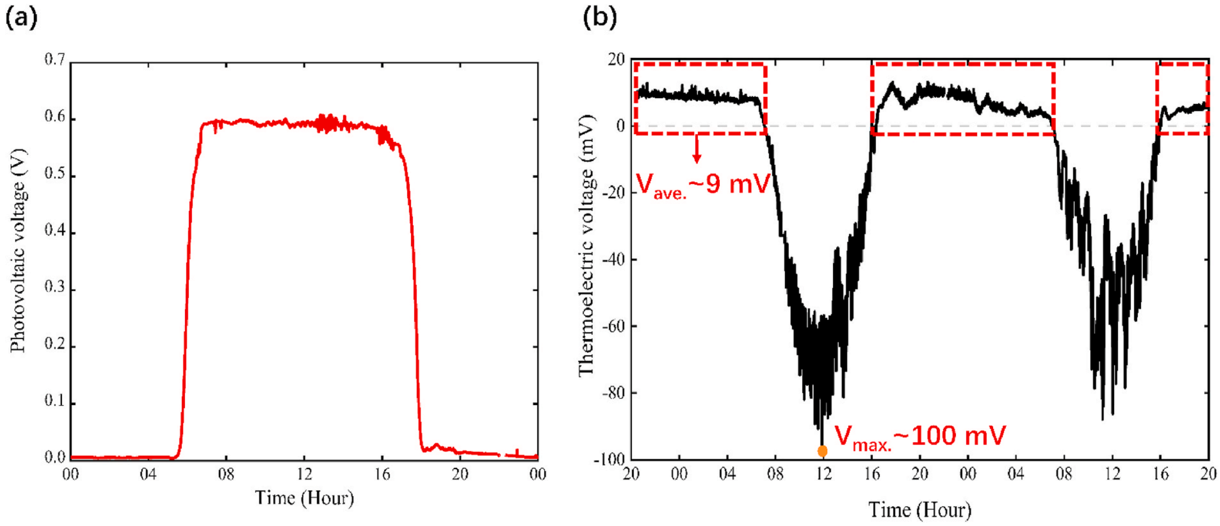


Fig. 5. (a) The open-circuit voltage of the PV module. (b) The open-circuit voltage of the TE device.

day and night. The most important information is that there exists output voltage of the TE at night when the sky is filled with darkness, which demonstrates that the PV-TE device can generate electricity at nighttime and this is exactly the contribution of the radiative cooling of the PV module and the Seebeck effect of the TE device. It can be found from the voltage curve that the output of the TE device is stable with an average output voltage of approximately 9 mV on the first night, while the output voltage exists a little fluctuation during the next nights and this may be caused by the unstable wind speed. When the wind speed increases, the cooling loss of the PV module increases passively, which will decrease the temperature difference between the ends of the TE device, corresponding to the reduction of the output voltage. The detailed information can be found in our previous work [20].

In the nighttime, the temperature difference of the TE device is generated by the radiative cooling of the PV module, which results in the electricity output of the device. So, the heat and cold source of the TE device is ambient air and the cold universe, respectively. In the daytime, the TE device is driven by the solar absorption of the PV module and the heat and cold source of the TE device are changed to be the sun and ambient air respectively. As shown in Fig. 5(b), compared with the voltage generated at night, the output voltage of the TE device increases with the increase of solar irradiance in the inverse direction. The maximum output voltage reaches nearly 100 mV at noontime when the solar irradiance is at a high level.

Notably, it can be seen from Fig. 5(b) that the output voltage of the TE device will drop to zero at the moment of the day (night) topples into the night (day), which is similar to the experimental results reported in Ref. [18]. Because some applications may request a continuous power supply, if the electricity output of the device drops to zero, it may cause negative effects on applications. Furthermore, there exists a difference in voltage polarity of the PV-TE device in the daytime and nighttime. For the application that is sensitive to the above voltage properties, if we want to eliminate the negative effect of the above voltage properties, there are two technical routes. The first one is that the PV-TE device can work for different applications in the daytime and nighttime so that both the voltage drop to zero and the difference in voltage polarity can be fully avoided. The second one is that the PV-TE device can be further improved to eliminate the difference in voltage polarity and make the voltage always higher than zero. For the second route, we propose a new PV-TE configuration for continuous power generation. As shown in Fig. 6, the new PV-TE configuration consists of solar cells, a TE device, a radiative cooler, and a reflective concentrator. The radiative cooler integrated into this configuration needs to have high solar reflectivity and strong thermal emission, such as photonic emitter [14] and metamaterials [30]. In the daytime, solar irradiance is reflectively concentrated on the solar cell for PV conversion due to the high reflective effect of the concentrator. Besides, the waste heat of solar cell is used for TE power generation and the remaining heat is dissipated to the

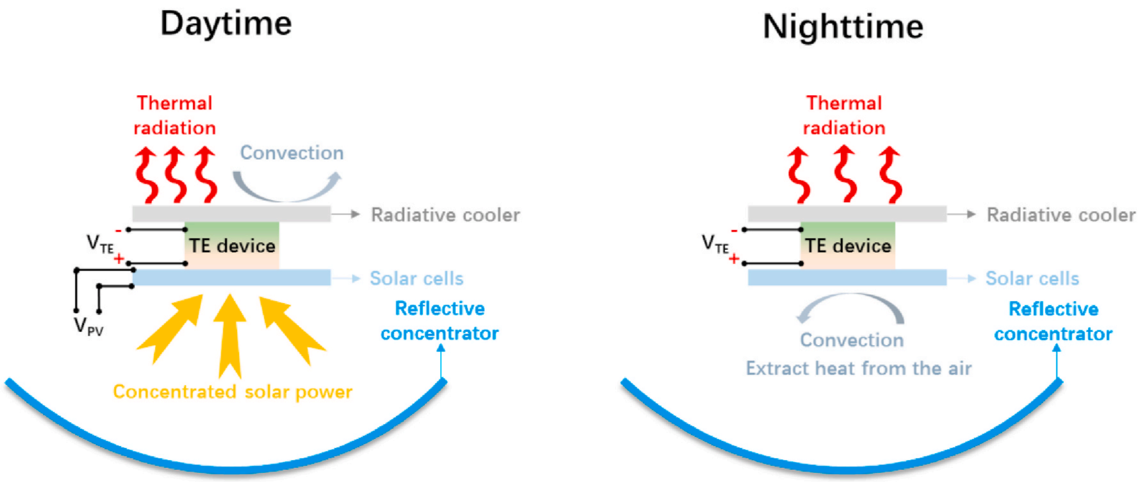


Fig. 6. Schematic of a new configuration of the PV-TE device for continuous power generation.

environment simultaneously by convection and the cold universe by radiative cooling, which indicates that the direction of heat flux passing through the TE device is from the solar cell to the radiative cooler. In the nighttime, the temperature of the radiative cooler is passively reduced due to the radiative cooling and a temperature difference between the radiative cooler and solar cell occurs and the heat flux extracted from the ambient air is also transferred from the solar cell to radiative cooler, which induces the power generation of the TE device. Therefore, this configuration ensures the PV-TE device can generate power during the day and night continuously without making the voltage drops to zero and producing voltage polarity, which is a good feature for applications that needs all-day power supply. Furthermore, the use of a reflective concentrator and high-performance radiative cooler are feasible solutions to improve the output power of the PV-TE device.

4. Summary

In this work, an experimental demonstration of generating power based on the PV-TE device at night is designed and conducted. The cold universe, a significant renewable thermodynamic resource, is connected with the ambient environment using the radiative cooling of the PV module (or the glass cover), which is the only one drive force for power generation using the Seebeck effect of the TE device at night. Although the averaged output voltage of the PV-TE device is measured just as approximately 9 mV at night, it proves that the PV-TE device can generate electricity from the darkness. Moreover, a novel configuration of the PV-TE device for continuous all-day power generation is conceptually designed for deep consideration. Importantly, this work provides a new solution for nighttime and all-day power generation applications, including low-power monitors, sensors, and lights.

CRediT authorship contribution statement

Bin Zhao: Supervision, Project administration, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, conceived the idea and supervised the project; performed the experiments; performed data analysis; wrote and reviewed the paper. **Mingke Hu:** performed the experiments. **Xianze Ao:** performed the FTIR characterization. **Qingdong Xuan:** Data curation, Formal analysis, performed data analysis. **Zhiying Song:** Data curation, Formal analysis, performed data analysis. **Gang Pei:** Supervision, project administraction, Writing – original draft, Writing – review & editing, conceived the idea and supervised the project; wrote and reviewed the paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the project funded by China Postdoctoral Science Foundation (2020TQ0307 and 2020M682033), the National Natural Science Foundation of China (NSFC 51776193 and 51761145109), and Fundamental Research Funds for the Central Universities.

References

[1] P.G.V. Sampaio, M.O.A. González, Photovoltaic solar energy: conceptual framework, Renew. Sustain. Energy Rev. 74 (2017) 590–601, https://doi.org/10.1016/j.rser.2017.02.081.

[2] W. He, G. Zhang, X. Zhang, J. Ji, G. Li, X. Zhao, Recent development and application of thermoelectric generator and cooler, Appl. Energy 143 (2015) 1–25, https://doi.org/10.1016/j.apenergy.2014.12.075.

[3] G. Li, S. Shittu, T.M.O. Diallo, M. Yu, X. Zhao, J. Ji, A review of solar photovoltaic-thermoelectric hybrid system for electricity generation, Energy 158 (2018) 41–58, https://doi.org/10.1016/j.energy.2018.06.021.

[4] S. Shittu, G. Li, X. Zhao, J. Zhou, X. Ma, Y.G. Akhlaghi, Experimental study and exergy analysis of photovoltaic-thermoelectric with flat plate micro-channel heat pipe, Energy Convers. Manag. 207 (2020), 112515, https://doi.org/10.1016/j.enconman.2020.112515.

[5] S. Soltani, A. Kasaeian, A. Lavajoo, R. Loni, G. Najafi, O. Mahian, Exergetic and enviromental assessment of a photovoltaic thermal-thermoelectric system using nanofluids: indoor experimental tests, Energy Convers. Manag. 218 (2020), 112907, https://doi.org/10.1016/j.enconman.2020.112907.

[6] W.G.J.H.M. van Sark, Feasibility of photovoltaic – thermoelectric hybrid modules, Appl. Energy 88 (2011) 2785–2790, https://doi.org/10.1016/j.apenergy.2011.02.008.

[7] S. Shittu, G. Li, X. Zhao, J. Zhou, X. Ma, Y.G. Akhlaghi, Experimental study and exergy analysis of photovoltaic-thermoelectric with flat plate micro-channel heat pipe, Energy Convers. Manag. 207 (2020), 112515, https://doi.org/10.1016/j.enconman.2020.112515.

[8] G. Li, K. Zhou, H. Liu, Simulation and experiment of a PV-MCHP-TE system and ambient parameters impacts, Int. J. Energy Res. 44 (2020) 4595–4604, https://doi.org/10.1002/er.5240.

[9] D.N. Kossyvakis, G.D. Voutsinas, E.V. Hristoforou, Experimental analysis and performance evaluation of a tandem photovoltaic–thermoelectric hybrid system, Energy Convers. Manag. 117 (2016) 490–500, https://doi.org/10.1016/j.enconman.2016.03.023.

[10] O. Rejeb, S. Shittu, C. Ghenai, G. Li, X. Zhao, M. Bettayeb, Optimization and performance analysis of a solar concentrated photovoltaic-thermoelectric (CPV-TE) hybrid system, Renew. Energy 152 (2020) 1342–1353, https://doi.org/10.1016/j.renene.2020.02.007.

[11] X. Ju, Z. Wang, G. Flamant, P. Li, W. Zhao, Numerical analysis and optimization of a spectrum splitting concentration photovoltaic–thermoelectric hybrid system, Sol. Energy 86 (2012) 1941–1954, https://doi.org/10.1016/j.solener.2012.02.024.

[12] A.P. Raman, W. Li, S. Fan, Generating light from darkness, Joule 3 (2019) 2679–2686, https://doi.org/10.1016/j.joule.2019.08.009.

[13] B. Zhao, M. Hu, X. Ao, N. Chen, G. Pei, Radiative cooling: a review of fundamentals, materials, applications, and prospects, Appl. Energy 236 (2019) 489–513, https://doi.org/10.1016/j.apenergy.2018.12.018.

[14] A.P. Raman, M.A. Anoma, L. Zhu, E. Rephaeli, S. Fan, Passive radiative cooling below ambient air temperature under direct sunlight, Nature 515 (2014) 540–544, https://doi.org/10.1038/nature13883.

[15] L. Zhu, A. Raman, S. Fan, Color-preserving daytime radiative cooling, Appl. Phys. Lett. 103 (2013), 223902, https://doi.org/10.1063/1.4835995.

[16] L. Zhu, A.P. Raman, S. Fan, Radiative cooling of solar absorbers using a visibly transparent photonic crystal thermal blackbody, Proc. Natl. Acad. Sci. 112 (2015) 12282–12287, https://doi.org/10.1073/pnas.1509453112.

[17] E. Mu, Z. Wu, Z. Wu, X. Chen, Y. Liu, X. Fu, Z. Hu, A novel self-powering ultrathin TEG device based on micro/nano emitter for radiative cooling, Nano Energy 55 (2019) 494–500, https://doi.org/10.1016/j.nanoen.2018.10.057.

[18] S. Ishii, T.D. Dao, T. Nagao, Radiative cooling for continuous thermoelectric power generation in day and night, Appl. Phys. Lett. 117 (2020), 013901, https://doi.org/10.1063/5.0010190.

[19] L. Fan, W. Li, W. Jin, M. Orenstein, S. Fan, Maximal nighttime electrical power generation via optimal radiative cooling, Opt Express 28 (2020) 25460, https://doi.org/10.1364/OE.397714.

[20] B. Zhao, G. Pei, A.P. Raman, Modeling and optimization of radiative cooling based thermoelectric generators, Appl. Phys. Lett. 117 (2020), 163903, https://doi.org/10.1063/5.0022667.

[21] Z. Xia, Z. Zhang, Z. Meng, L. Ding, Z. Yu, Thermoelectric generator using space cold source, ACS Appl. Mater. Interfaces 11 (2019) 33941–33945, https://doi.org/10.1021/acsami.9b10981.

[22] R.J. Parise, G.F. Jones, Energy from deep space the nighttime solar cell/sup TM/ electrical energy production (Cat. No.00CH37022), in: Collect. Tech. Pap. 35th Intersoc. Energy Convers. Eng. Conf. Exhib, American Inst. Aeronaut. & Astronautics, 2018, pp. 139–147, https://doi.org/10.1109/IECEC.2000.870653.

[23] D. Zhao, A. Aili, Y. Zhai, S. Xu, G. Tan, X. Yin, R. Yang, Radiative sky cooling: fundamental principles, materials, and applications, Appl. Phys. Rev. 6 (2019), 021306, https://doi.org/10.1063/1.5087281.

[24] J. Mandal, Y. Fu, A.C. Overvig, M. Jia, K. Sun, N.N. Shi, H. Zhou, X. Xiao, N. Yu, Y. Yang, Hierarchically porous polymer coatings for highly efficient passive daytime radiative cooling, Science 80 (362) (2018) 315–319, https://doi.org/10.1126/science.aat9513.

[25] T. Li, Y. Zhai, S. He, W. Gan, Z. Wei, M. Heidarinejad, D. Dalgo, R. Mi, X. Zhao, J. Song, J. Dai, C. Chen, A. Aili, A. Vellore, A. Martini, R. Yang, J. Srebric, X. Yin, L. Hu, A radiative cooling structural material, Science 80 (364) (2019) 760–763, https://doi.org/10.1126/science.aau9101.

[26] W. Li, S. Fan, Radiative cooling: harvesting the coldness of the universe, Opt Photon. News 30 (2019) 32, https://doi.org/10.1364/OPN.30.11.000032.

[27] M. Rubin, Optical properties of soda lime silica glasses, Sol. Energy Mater. 12 (1985) 275–288, https://doi.org/10.1016/0165-1633(85)90052-8.

[28] L. Zhu, A. Raman, K.X. Wang, M.A. Anoma, S. Fan, Radiative cooling of solar cells, Optica 1 (2014) 32–38, https://doi.org/10.1364/OPTICA.1.000032.

[29] B. Zhao, M. Hu, X. Ao, Q. Xuan, G. Pei, Comprehensive photonic approach for diurnal photovoltaic and nocturnal radiative cooling, Sol. Energy Mater. Sol. Cells 178 (2018) 266–272, https://doi.org/10.1016/j.solmat.2018.01.023.

[30] Y. Zhai, Y. Ma, S.N. David, D. Zhao, R. Lou, G. Tan, R. Yang, X. Yin, Scalable-manufactured randomized glass-polymer hybrid metamaterial for daytime

radiative cooling, Science 80 (355) (2017) 1062–1066, https://doi.org/10.1126/science.aai7899.