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Concepts for heat utilization and passive cooling techniques to improve reliability and performance of Building Integrated Photovoltaics (BIPV)

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Abstract. When integrated into urban environments, photovoltaic (PV) systems usually present operational temperatures that are significantly higher than those shown by rack-mounted systems. High operating temperatures are associated with reduced reliability of PV modules and significantly impact the electrical performance of solar cells. Utilizing the heat produced on PV modules or reducing operating temperatures can bolster their application within the building sector. We present the three main concepts studied to achieve these goals. First, a PV is a chimney concept that allows the use of the heat generated by the modules. Simulations for a PV chimney installed on a building in the Netherlands showed that although the heat quality produced inside its cavity was low, the potential use of the air mass flow for ventilation applications is promising. Additionally, we present two passive cooling solutions that can reduce the operating temperatures of PV modules: Optical filters and phase change materials. Experimental measurements in Delft showed that these solutions reduce the operating temperature of PV modules between 4 °C to 20 °C, particularly under high irradiance hours.

1. Introduction

The energy transition toward a carbon-neutral society requires urban landscapes to transform from energy consumers to energy prosumers. This transformation requires that all the available surfaces of our infrastructure must also generate electricity and heat locally to meet, at least partially, their required energy demand. Building Integrated photovoltaics (BIPV) is one of the more attractive solutions to produce energy locally, and their potential in aiding the energy transition has been proven [1]. However, due to their unique layout, these systems usually present operational temperatures higher than their standard rack-mounted counterparts [2]. High temperatures reduce the photovoltaic (PV) module efficiency and can significantly impact their reliability [3]. In this work, we present an integration concept that aims to use the heat produced by integrated systems and discuss two potential passive cooling techniques that can help improve the performance and reliability of BIPV systems.

2. Concepts for heat utilization – The PV chimney concept

Heat production on PV systems can be substantial. Roughly speaking, a solar cell operating at 20% efficiency will dissipate 80% of the incident energy almost entirely as heat due to thermalization and non-absorption losses related to the band gap and optical properties of the absorber material deployed on the PV module. As stated before, PV modules on integrated systems, where their backside is usually insulated, produce more heat than their standard rack-mounted counterparts. One of the most common techniques developed to use this heat is the PV-Thermal module, which consists of a pipeline design attached to the backside of the module through which water or coolant circulates. However, this layout requires external energy to feed the pumps required by the system. On the PV chimney concept, we investigate the potential use of this heat without the need for any additional energy.

The PV chimney concept consists of the combination of a naturally ventilated façade with an integrated PV system. On the former, the temperature gradient of the air contained within the cavity creates buoyancy effects that produce an airflow sufficiently high for ventilation purposes. The greater this gradient, the better airflow values obtained. The principle of operation of the PV chimney is using the heat produced by the PV modules to boost this buoyancy effect and study the quality of the heat produced to analyze its use in auxiliary systems of the building.

In its design stage, the PV chimney aimed toward a naturally ventilated façade combined with a PV system. The PV modules could be placed at the front, inside the cavity, or attached to the building. These different cavity layouts could potentially improve airflow, reduce the operating temperature of the modules, or increase the heat quality of the air. Figure 1 presents the schematics of the PV chimney concept (a) and the cavity layouts studied (b).

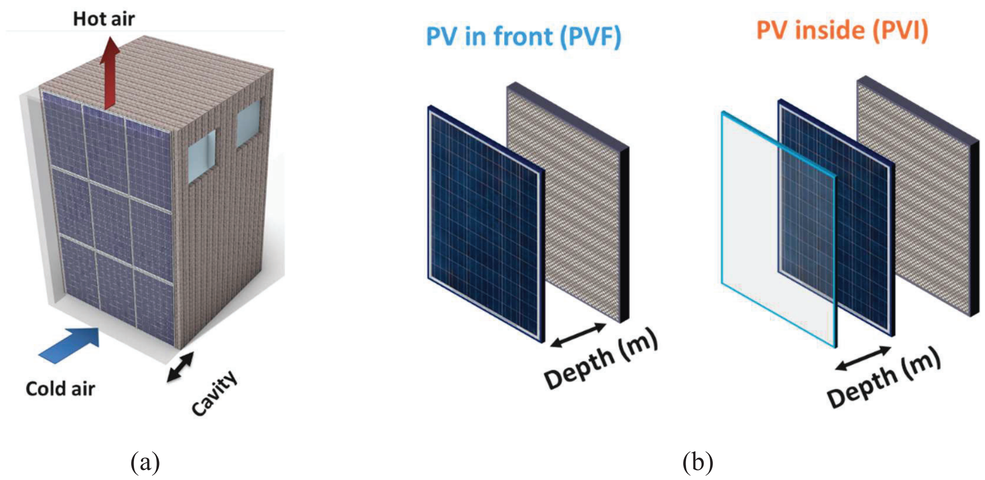


Figure 1 (a) Schematic of the PV Chimney concept, a combination of a naturally ventilated façade with an integrated PV system. The heat produced by the PV modules improves the airflow within the cavity of the façade, which provides natural ventilation. (b) The two cavity layouts were studied to analyze the energy potential of the system, with the PV modules acting as the front layer of the façade (PVF) or located behind a glass layer within the cavity (PVI)

2.1. Modeling and experimental validation

A simplified model of the PV chimney concept was manufactured and tested within the facilities of the Photovoltaics Materials and Devices (PVMD) group at TU Delft. The model consisted of the three main layers of the chimney (Glass / PV module / Medium Density Fireboard (MDF)). The measurements of each of these layers were 2.20 m in width and 1.02 m in height. These measurements fitted the size of the c-Si PV module selected for the experiment. Figure 2 shows the experimental setup utilized. In the laboratory, measurements of each layer's temperature, using T-type thermocouples, were done along their height to know the temperature gradient across the vertical direction. A AAA steady-state solar simulator provided the irradiance for the tests, and cavity air flow and temperature were also measured. All the details of the experiments are available in [4]

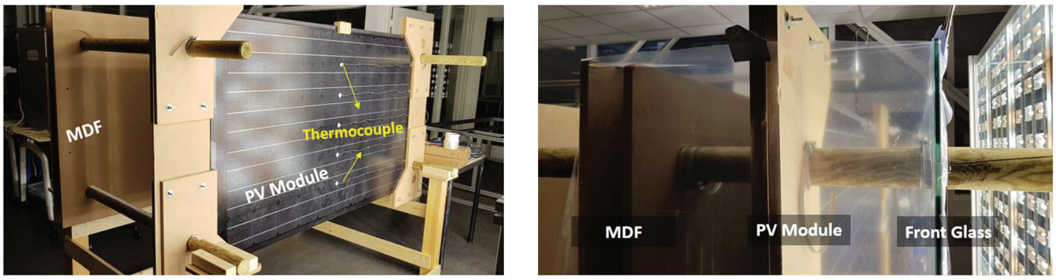


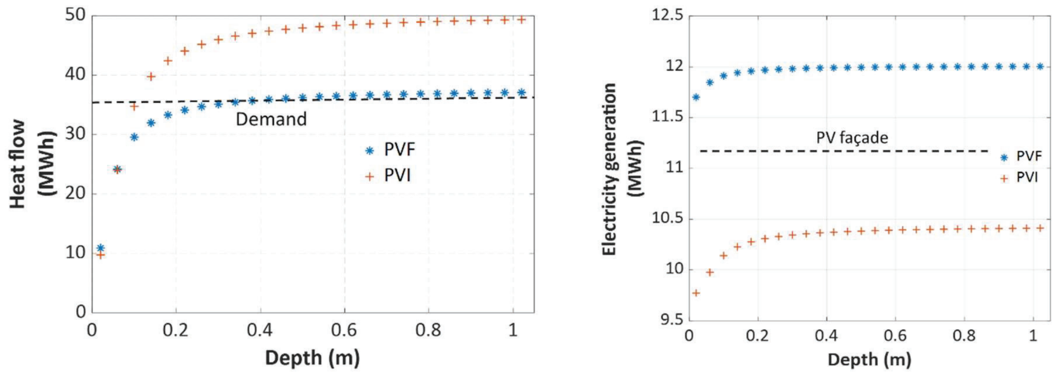
Figure 2 Simplified demonstrator of the PV chimney concept. Each layer measured 2.2 m in width and 1.02 m in height; measures fitting the size of the c-Si PV module utilized. The Concept was studied under controlled conditions inside the PV laboratory of the PVMD group at TU Delft, using a AAA class solar simulator. On the left is a picture of the demonstrator as PVF. In this layout, the module acts as the front layer of the chimney. On the right is the PVI layout, with front glass, the PV module in the middle, and the building material on the backside.

From the obtained experimental data, a computational model was developed based on the finite volume approach for the different heat transfer mechanisms and a plume airflow model based on the works by He et al. [5]. These models' mathematical details are available in [4]. Comparing the values predicted by the models with experimental data, the temperature values had a relative RMSE value of 7%. As for the airflow, the RMSE value was 15%. The accuracy of the models for such complicated layouts was considered satisfactory, and sensitivity studies carried out to optimize the design of the PV chimney followed.

2.2. *Simulation results*

The sensitivity analysis studied the case of a four-story building located in Amsterdam, NL. The entire PV façade consists of a 10 m x 10 m size, with the system covering the entire area. The living spaces had a size equal to 100 m^2. All the simulation details regarding the building materials considered are available in the work of Wapperom [6]. The heating demand and the electricity demand were 35 MWh/year and 18.2 MWh/year, respectively, per the city's requirements [7].

The calculated optimal cavity size of the chimney was 0.2 m. For this cavity size, the heat flow produced by the chimney for both considered layouts (PVF and PVI) could potentially supply de demand of the building, as shown in Figure 3(a). A similar sensitivity analysis of the yearly electrical yield was done for both cavity layouts. As with heat generation, the electricity yield reaches a maximum for a cavity depth of around 0.2 m (Figure 3(b)). Increasing the depth further does not significantly improve both yields. As far as cavity layouts are concerned, placing the PV system as the front layer of the chimney increased the annual electrical yield by 6% compared to a standard integrated PV façade. Placing the PV modules inside the cavity increases the heat yield but decreases the electrical yield by 8%. The main reasons for this loss are the increased reflective losses from the front glass layer and an increased temperature of the modules inside the cavity [6].



(a) (b)

Figure 3 (a) Yearly heat flow generated by the PV chimney for different cavity depths for both the PVF and the PVI layouts compared to the simulated heat demand of the building (dashed line). (b) Yearly electricity generation of the PV system of the chimney for both cavity layouts compared with the yield produced by a standard PV façade under the same conditions.

Despite the exciting potential of the complete supply of the heat demand, the quality of the heat created in the cavity was insufficient for any practical application; the minimum temperature that the air should reach to make it suitable must be 45°C as established by [6], neither cavity layout could achieve this value. However, the air change rate (ACH) produced by the chimney, particularly in the PVI layout, exceeded the ventilation demands of the building and could produce energy savings amounting to 0.8 MWh/year [6], as shown in Figure 4.

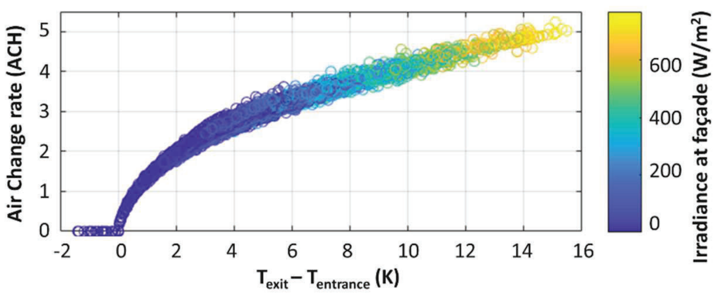


Figure 4 Air Change Rate (ACH) of the PV chimney as a function of the difference in air temperature between the inlet and the outlet for different irradiance values. The PVI configuration can produce a higher ACH as ΔT_{air} presents values close to 8K

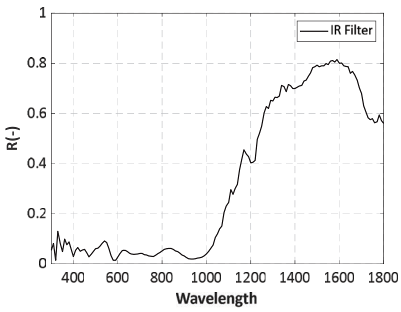
For best electrical performance, a PVF cavity of 0.2 m performs significantly better since the modules have lower operational temperatures and no additional optical losses. The PVI configuration could be further improved by adding passive cooling techniques for the PV modules, given its potential heat production. For this reason, two different passive cooling techniques were studied: Optical Filters and Phase Change Materials.

3. Concepts for passive cooling – Optical Filters

Optical filters are devices that selectively reflect or transmit light at any given wavelength using the interference principle. Thanks to powerful mathematical techniques, these devices can be designed for almost any reflective pattern desired. For those interested in the physics, mathematical modeling, and the materials most often used, we recommend the seminal work of Mcleod [8]

In her work, Seoane da Silva [9] estimated the temperature increase on a c-Si solar due to different wavelengths of light under Nominal Operational Cell Temperature NOCT [10] conditions. It was estimated that by reflecting light in the Infrared (IR) wavelengths ranging from 1130 nm to 1650 nm, the operating temperature of the solar cell could be lowered by up to 5 °C. Since c-Si solar cells do not use light at these wavelengths for electricity production, reflecting this portion of the solar spectrum could improve the electrical output.

3.1. Filter design
Reflecting light at wavelengths within the IR requires specific design techniques referred to as second-order optimization. Details of these techniques are out of the scope of this work. Interested readers can consult the work by Tikhonravov [11]. The materials selected to manufacture the filter were Silicon nitride (Si_4N_3) and Silicon Dioxide (SiO_2), commonly used in the PV industry as anti-reflective coatings and passivation layers and whose deposition techniques are well known and utterly compatible on an industrial scale. Some reflection on the visible spectrum was allowed to keep the maximum number of layers required to 17 and a relatively low value of the thickness of 1.5 μm.



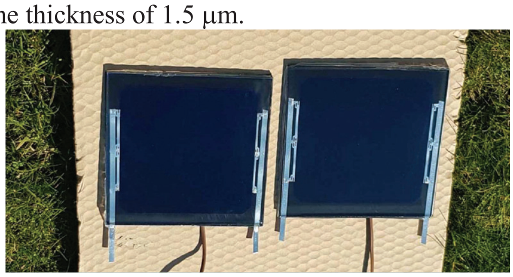


Figure 5(a) Estimated reflectance of the IR filter (b) A PV mini-module with and without implementation of the IR filter.

Figure 5(a) shows the estimated reflectance produced by the manufactured filter. For the wavelength range of interest, light reflection has an average value of 65%. Once deposited on a PV mini-module (Figure 5(b)), the filter is virtually indistinguishable from standard glass.

3.2. Modeling and experimental validation
With the final design of the filter ready, a complete computational model is developed to predict its performance. This prediction implies peculiar modeling challenges, as optical filters have particular spectral behavior that changes depending on the angle of incidence of light. All the mathematical details of the spectral and thermal models can be found in [12].

Thermal simulations showed that the computational models accurately predict the operational temperature of a standard PV module under NOCT conditions (44 °C) with a relatively small error compared to the value established by the cell manufacturer (44.5 °C). According to simulations, the effect of the IR filter reduces the operating temperature under the same conditions by four degrees celsius, which also goes in accordance with measurements taken in the PVMD PV laboratory using the AAA steady-state solar simulator and the findings of Seoane da Silva [9]. Moreover, the model can predict the gradient of temperatures within the module; these gradients are also in line with findings observed in the literature [13]

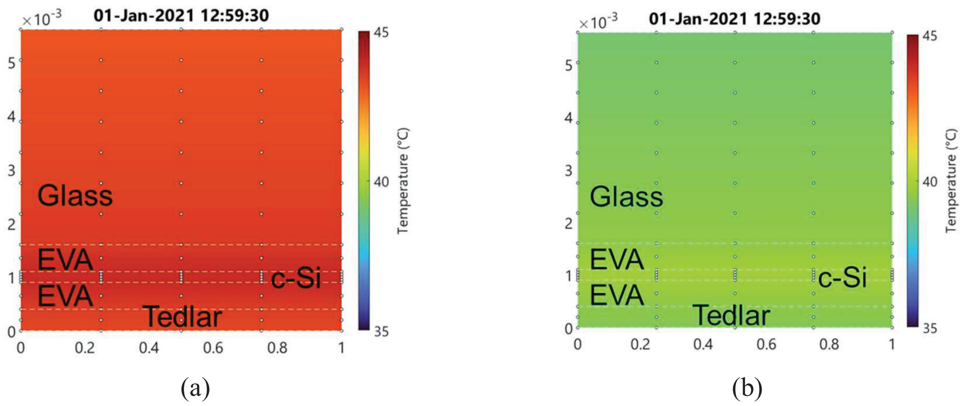


Figure 6 (a) Temperature distribution of a standard c-Si module under NOCT conditions. The temperature gradient at steady-state conditions is 1.2 °C, a value found in other studies' observations [13]. (b) Under the same conditions, the design IR filter's implementation reduces the module's operating temperature by 4 °C, performance close to the ideal 5 °C as found by [9]).

Currently, outdoor testing is underway on the PV monitoring facility of TU Delft. Several c-Si solar cell topologies will be studied, as their IR behavior is different depending on their architecture (see the work of Vogt et al. [14]). Further findings will be publicly available at the end of the experimental activities.

4. Concepts for passive cooling – Phase change materials

While IR filters have proved to reduce the operating temperature of PV modules, their cooling potential remains limited. Phase change materials (PCM) represent a desirable alternative to passively cooling solar modules.

As their name suggests, PCMs are manufactured with solutions that change from one phase to another (usually solid to fluid and back) when reaching a given temperature threshold. During the change phase, the material remains at a constant temperature, which makes it a very effective heat sink. Theoretically, attaching a PCM to a PV module could provide effective thermal management by maintaining a considerably lower module temperature by using the heat produced to continue the change phase process.

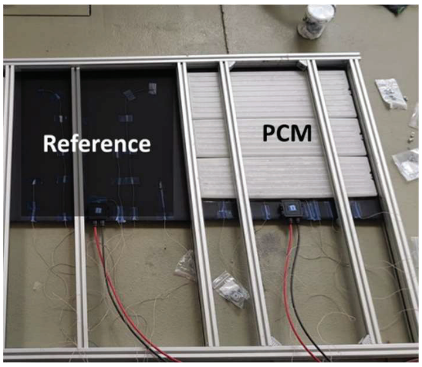
4.1. Phase change material selection

PCMs can be classified based on their melting temperature and their latent heat. The former indicates at which temperature the material starts changing its phase, and the latter indicates its potential to store heat [15]. Ideally, for a PV application, a PCM should have melting temperatures ranging from 20 °C to 30 °C since modules usually operate at temperatures up to 60 - 70 °C, although this varies significantly for different locations, applications, and other conditions. Additionally, the latent heat should be high to provide thermal management for prolonged periods during the day. A small latent heat value means the PCM will melt quickly; therefore, thermal management is guaranteed only for a short period.

The company OC Autarkis [16] kindly provided PCM slabs manufactured using salt hydrates. These PCM slabs have a melting temperature of 26 °C with a latent heat of 180 KJ/L, making them ideal for PV applications.

4.2. Modeling, experimental validation, and thermal management potential.

Two 60 cm x 60 cm mini-modules were manufactured for testing based on highly efficient SunPower IBC Gen2 solar cells [17]. Both modules had identical performance under the AAA solar simulator, with an illuminated area efficiency of 19.9% and a maximum power of 48.7 W. On one of the modules, three PCM slabs were mechanically attached, whereas the other one was monitored as a reference module (see Figure 7(a)). Both modules were installed on the PV monitoring facilities at TU Delft for long-term monitoring (see Figure 7(b)). Both modules were insulated on the backside using Armaflex® with 19 mm thickness.



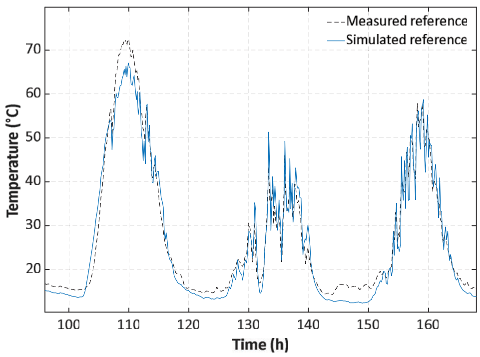
(a)

(b)

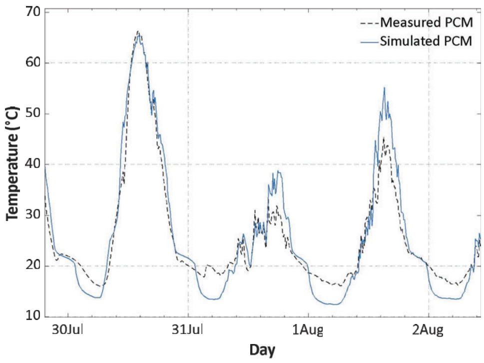
Figure 7(a) photographs the backside of the manufactured PV mini-modules for testing with the PCM slabs that are mechanically attached to one of them. (b) The IBC mini-modules, when installed on a tilted plane at an angle equal to 35°, have an appealing aesthetic aspect, with a homogeneous color and the cells barely visible.

A 1-D thermal model was produced by Verheijen [18], Nierop & Sanchez [19], and Mooij [20] and compared with the average measured temperatures of 6 thermocouples placed across each module. The model predicted the temperature of the standard module with a relative RMSE error of 6% during the daytime (see Figure 8(a)). For the case of the module with the PCM slabs, the relative RMSE error of the model was 7% (see Figure 8(b)).

Long-term monitoring showed that, during the summer, the PCM had a substantial cooling potential with temperature reductions that went up to 21 °C. As Figure 9 shows, thermal management starts during the morning and peaks early in the afternoon. Afterward, the PCM slabs melt entirely, and the temperatures of the modules are almost identical to one another. During the evening, the stored heat on the PCM starts to be released towards the PV module, producing a slightly higher temperature than the standard case.



(a)



(b)

Figure 8 Comparison between the measured and simulated temperature for (a) a standard PV module with its backside insulated and (b) a PV module with PCM slabs mechanically attached to its backside, also with insulation.

The power produced by the mini-modules was measured during the entire experiment. Results showed that owing to its cooling potential, the module with the PCM slabs had up to 8% more energy yield in the warmest months of 2020 (June – August), representing a substantial performance improvement thanks to thermal management.

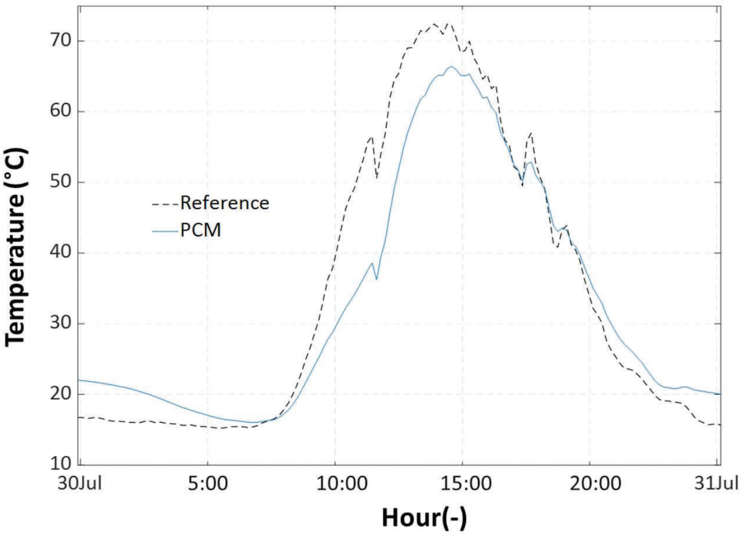


Figure 9 Comparison during a warm day (30th of July) of the temperatures of the standard (dashed line) and the PV + PCM module (blue line). The use of PCM produces significant thermal management during the morning up to early in the afternoon.

5. Conclusions

In terms of thermal energy, a PV chimney with a PVI layout increases the heat generation significantly. However, the heat quality of the air on this layout was insufficient for any practical application. The air mass flow produced inside the cavity, however, showed promising results for ventilation purposes.

Overall, for the weather conditions of the Netherlands, simulations of the PVF layout presented an increase in the electrical yield by 6% when compared to a standard vertical PV façade. Simulations of the PVI layout showed an electrical yield reduction of 8% under the same conditions. These results place the PVF layout as the best option from an energetic point of view.

To reduce the operating temperatures of the PV modules, we carried out simulation and experimental work on two passive cooling solutions. The first option was the design of optical filters that reject unwanted IR radiation that can increase the temperature of the PV module without any contribution to its electrical performance. Implementation of a simple IR filter that rejects light at wavelengths between 1130 nm and 1800 nm reduced the operating temperature of PV modules by up to 4°C under NOCT conditions. Currently, Outdoor testing is underway to estimate its potential under varying weather conditions.

The second alternative was the use of phase change materials (PCM). When mechanically attached to a PV module, PCM slabs based on salt hydrates could provide substantial thermal management of the PV modules with observed operating temperature reductions of up to 20°C. Measurements showed that these reduced temperatures occur during the sunniest hours of the day.

Both cooling options operate under different physical mechanisms, and their combination can improve the thermal management of PV modules. These solutions could work on any integrated PV system and may have additional advantages in terms of HVAC demand savings since they can also reduce the indoor temperature of living spaces. Further studies will account for all these potential benefits.

References

[1] C. Ballif, L.-E. Perret-Aebi, S. Lufkin and E. Rey, "Integrated thinking for photovoltaics in buildings," *Nature Energy,* vol. 3, pp. 438-442, 2018.

[2] J. Goncalves, T. van Hooff and D. Saelens, "Performance of BIPV modules under different climatic conditions," in *4th International Conference on Energy, Environments, and Economics*, Edinburgh, 2019.

[3] A. Ndiaye, A. Charki, A. Kobi, C. Kebe, P. Ndiaye and V. Sambou, "Degradations of silicon photovoltaic modules: A literature review," *Solar Energy,* vol. 96, pp. 140-151, 2013.

[4] J. Ortiz Lizcano, Z. Haghighi, S. Wapperom, C. Ferreira, O. Isabella, A. Dobbelsteen and M. Zeman, "Photovoltaic chimney: Thermal modeling and concept demonstration for integration in buildings," *Progress in Photovoltaics: Research and Applications.,* no. 28, pp. 465-482, 2019.

[5] G. He, J. Zhang, and S. Hong, "A new analytical airflow model for airflow solar chimneys based on thermal boundary layers," *Solar Energy,* no. 136, pp. 614-621, 2016.

[6] S. Wapperom, "Energetic performance of a combined double skinfaçade with photovoltaic modules placed at various locations," TU Delft repository, Delft, 2019.

[7] Liander, "Open Datta," [Online]. Available: https://www.liander.nl/partners/datadiensten/open-data/data. [Accessed 08 08 2019].

[8] A. Mcleod, Thin-Film Optical Filters, CRC Press, 2017.

[9] P. Seoane da Silva, "Infrared optical filters for passive cooling of crystalline silicon modules," TU Delft repository, Delft, 2017.

[10] IEC, "IEC 61215-1/2:2021 Terrestrial photovoltaic (PV) modules - Design qualification and type approval," IEC, 2021.

[11] A. V. Tikhonravov, M. K. Trubetskov, and G. W. DeBell, "Optical coating design approaches based on the needle optimization technique," *Applied Optics,* vol. 46, no. 5, pp. 704-710, 2007.

[12] J. Ortiz Lizcano, P. Procel, A. Calcabrini, G. Yang, A. Ingenito, R. Santbergen, M. Zeman and O. Isabella, "Colored optic filters on c-Si IBC solar cells for building integrated photovoltaic applications," *Progress in Photovoltaics,* vol. 30, no. 4, pp. 401-435, 2021.

[13] S. Aly Pamir, S. Ahzi, N. Barth and B. Figgis, "Two-dimensional finite difference-based models for couple irradiation and heat transfer in photovoltaic modules," *Solar Energy Materials and Solar Cells,* vol. 180, pp. 289-302, 2018.

[14] M. Vogt, H. Holst, M. Winter, R. Brendel, and P. Altermatt, "Numerical modeling of c-Si PV modules by coupling the semiconductor with the thermal conduction, convection and radiation equations," *Energy Procedia,* vol. 77, pp. 215-224, 2015.

[15] H. Mehling and L. F. Cabeza, Heat and cold storage with PCM, Springer, 2008.

[16] Orange Climate Autarkis, "Orange Climate," [Online]. Available: https://www.orangeclimate.com/nl/ocautarkis. [Accessed 20 12 2021].

[17] SunPower, "Maxeon GenII Solar Cells," SunPower, 2020.

[18] M. Verheijen, "Thermal management of photovoltaics using phase change materials," TU Delft repository, Delft, 2019.

[19] C. van Nierop & Sanchez, "Phase Change Materials for thermal management of PV modules," TU Delft repository, Delft, 2019.

[20] C. de Mooij, "A Spectrally Resolved Model for a PV + PCM System," TU Delft repository, Delft, 2020.