Passive Cooling of Photovoltaic Modules in Qatar by Utilizing PCM-Matrix Absorbers

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Abstract

Operation of solar PV systems under extremely high temperatures and high humidity in hot climates represents one of the major challenges to guarantee higher system's reliability. Therefore, thermal management in hot climates is crucial for reliable application of PV systems, as it has a potential to increase the efficiency and life expectancy and to stabilize the output power characteristics. On the other side, dust accumulation on PV module together with atmospheric water vapor condensation may cause a thick layer of mud that is difficult to be removed. The present research focuses on utilization of Phase Change Materials (PCM) for passive thermal management of solar systems. Passive cooling uses the high temperature differences between day and night in arid desert regions, due to sky radiation in the night. The high thermal capacity of PCM accumulates coolness during night to keep the PV cells at a moderate temperature during the day. This also can help maintaining the PV panel temperature well above the dew point to prevent condensation during day and night, thereby avoiding mud formation on the panel surface, which reduces water consumption and mechanical efforts in cleaning. Initially the passive cooling concept has been examined with one type of solar PV panels; Monocrystalline, with two thicknesses of PCM Absorber; 30 mm and 50 mm, melting point of 54°C and another arrangement with heat fins in place of the PCM layer, where both arrangements are compared with a reference PV module with no cooling devices attached to it. The experimental campaign has been conducted at the outdoor testing facility under weather conditions in Qatar for nine months from April to December 2018. The experimental analysis showed that the PV module's peak temperature was shaved by 10 °C with the PCM effect compared to reference PV modules without PCM. The experimental analysis confirmed the results of the numerical optimization, which revealed that there is an optimum thickness for PCM layer ~ 20-30 mm at 54 °C melting point. The analysis has revealed that cooling mechanism with heat fins alone (without PCM) achieved a temperature shaving of 5-8 °C. Moreover, the module peak temperature can be shaved at a constant temperature for a longer time with higher PCM thickness during noontime and remains at the same as the PCM melting temperature for five hours. Although the magnitude of peak shaving effect decreases with the higher thickness, stabilized temperature for longer time around the noontime can have a positive impact on stabilized power supply that is important for grid operation when installing large capacities of solar PV. It is worth mentioning that a numerical simulation model has been developed in parallel, and validated against measurements under real operation conditions of PV modules in Qatar, to examine the effect of the PCM-Matrix Absorber (PCM-MA) on solar PV systems and optimize its properties for Qatar. For the optimized PCM-MA, which has been arrived at later after manufacturing the pilot plant, the PV module temperature is reduced by 23 °C, the energy yield can increase by 9-11% for mono and polycrystalline PV modules and 6-8% for thin film modules depending on the temperature coefficient of the high quality modules available in the international market. Presentation of the numerical simulation model and results will be elaborately discussed in a following publication.

Keywords: Passive Cooling of PV, Operation of PV in desert, PV Efficiency, Solar Power, hybrid PV-T

1. Introduction

It is well known that considerable degradation in the electrical efficiency and life time of PV modules takes place with the increase in the panel temperature, which is the biggest challenge for reliable operation of PV systems in hot and desert climates. This fact has triggered scientists and research institutions to propose and test

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different cooling techniques both numerically and experimentally as well as improving PV cells characteristics to reduce the temperature coefficient, which correlates the magnitude of efficiency drop against the module's temperature. These techniques include both passive and active cooling. Active cooling relies water or air cooling, with forced air draft and water circulation techniques. Passive cooling techniques include conductive cooling, e.g. with heat fins for extending heat transfer surfaces with ambient, and using phase-change materials (PCM) as heat absorbers. In hot summer, air-cooling would be less effective as the ambient temperature reaches up to 50°C, hence water cooling or passive thermal management of PV cells become a necessity.

Enhancement of the PV module electrical efficiency depends mainly on the cooling technique, geographical location and the season of the year, type and size of the module, and usually corresponds with a rise of 3-5 % in overall efficiency [1] - [4].

Application of PCM for passive cooling, which can be realized by integration of a PCM layer as a heat absorber with the back side of PV panels, which shaves the peak temperature of PV modules during day time and helps maintaining the module temperature above the dew point, thereby preventing mud formation and cementation of dust on the modules. One of the main problems faced when using passive cooling is the strong dependency of natural cooling rate on ambient conditions, as high ambient temperature or low wind speed or combination of both significantly affect the cooling effectiveness of this method. Due to low thermal conductivity of PCM, which limits the power density during charging and discharging, it can be combined with highly conductive aluminum matrix absorber, which allows a significant enhancement of the PCM thermal conductivity [5].

Although passive cooling is simple and does not involve water or air circulation like active cooling, a large amount of incident energy on the solar PV module (usually more than 80%) is converted into heat, which reduces the electrical efficiency and is dissipated to the ambient as waste heat. Hence, a more efficient approach would be to harness such waste heat as useful thermal energy through active cooling with water or air, i.e. hybrid PV-Thermal (PV/T) collectors. As hybrid PV/T delivers both electrical and thermal energy simultaneously from the same device and land area, these units usually have a higher overall efficiency up to 85% and more in some designs, when compared with stand-alone PV modules or solar thermal collectors. This results in significant cost savings and requires less space per unit energy produced. Moreover, it can play a vital role in decarburization plans of energy systems, as the thermal energy/heat constitutes about half of total global energy demand. Solar heat offers key advantages over other renewable sources for meeting this demand through distributed, integrated systems [6]. However, PV/T may be viable only in areas where there is a demand for thermal energy, otherwise for desert based plants where this condition is not satisfied passive cooling should be more economically and technically viable.

The present research focuses on utilization of Phase Change Materials (PCM) for passive thermal management of solar PV systems. The main focus is to explore the effect of utilization of PCM-based cooling elements on the thermal behavior of solar PV modules. By attaching PCM-Absorbers to the back side of PV modules, the modules temperature can be regulated by the virtue of PCM to extract and accumulate heat at high density, as PCM have a high specific heat capacity due to latent heat of fusion during melting and solidification. Moreover, the PCM absorber can help reducing atmospheric water vapor condensation during night on the surface of PV module by releasing the absorbed thermal energy during the daytime to keep the PV module on a temperature above the dew point.

Some of the important advantages of the proposed solution include, simplicity, no moving parts such as coolant circulation pumps or air blowers are needed, low tech and can be manufactured locally from aluminum waste and oil waste, zero self-energy consumption, involves no hazards such as chemical toxicity, flammability or explosivity, and has a longer life time than the life span of top quality PV modules available in the international market.

The main focus of this paper is to present and discuss the experimental analysis on passive cooling of PV using PCM-Matrix Absorbers under real weather conditions in Qatar. The analysis examined the effect of main parameters of the PCM absorbers such as the PCM melting point, heat capacity or absorber thickness as well as the effect of using heat fins to extend the heat dissipation surface with the ambient.

2. Methodology

A pilot and outdoor experimental test setup has been designed, manufactured and installed at the Outdoor Solar Test Facility (OTF) of Qatar Foundation, in Qatar, where the system effectiveness and performance have been measured under the sun and experimental data has been analyzed for almost 9 months.

The commissioned modules include a PV reference module, PV module with phase change material 54°C melting temperature, 30 mm thickness attached to the back sheet, PV module with aluminum heat fins attached to the back sheet of the PV module and PV module with phase change material 54°C melting temperature, 50 mm thickness attached to the back sheet as shown in Figure. 1. All the PV modules are monocrystalline with specifications shown in Table. 1.

Figure 1: Outdoor Test Facility and Pilot Plant at the Outdoor Solar Test Facility of Qatar Foundation

Table 1: PV Module electrical characteristics

Characteristics	**Nominal values (Eco Line ES30M36)**
Maximum Power (Pmax) *	30 [W]
Short circuit current (Isc)	5.84 [A]
Open circuit voltage (Voc)	51.8 [V]
Maximum power current (i_{mpp})	1.78 [A]
Maximum power voltage (v_{mpp})	16.8 [V]
Temperature Coefficient (β_{ref})	-0.44 [%/°C]
Temperature Coefficient (β_v)	0.36 [%/°C]
Temperature Coefficient (β_i)	0.05 [%/°C]

3. Outdoor Testing Results

3.1 Pre-commissioning Testing in Germany

In order to test the functionality of the pilot plant, the system was pre-commissioned and tested in Germany before shipment to Qatar at the Fraunhofer-Institut für Fertigungstechnik und Angewandte Materialforschung (IFAM) (Fraunhofer-Institute for Manufacturing Technology and Advanced Materials), Branch Lab Dresden, Germany. The IFAM has developed a fibrous porous aluminum structures that has be used for enhancing heat transfer characteristics of the PCM-Matrix absorbers used in this study.

The pre-commissioned system has been examined under Sun in Germany on some of the hot days in summer 2017. The outdoor tests in Germany confirmed the research hypothesis and actual temperature reduction of PV modules by 10 °C even under climatic condition in Germany on one of the hot days as shown in figures 2 & 3.

Figure 2: Pre-commissioned PV system cooled with PCM Absorbers in Dresden, Germany

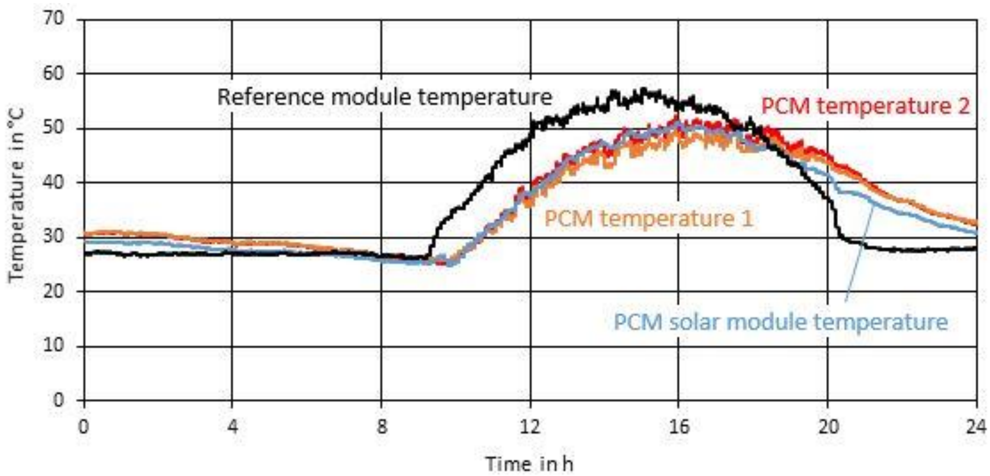

Figure 3: Sample of outdoor test results under Sun in Germany in June 2017

5.1 Outdoor Experimental Test Setup

The passive thermal management test setup has been designed installed and commissioned in Qatar end of March 2018. The measurements campaign and data collection started on 3rd of Apr 2018 up to date. One thermocouple is attached at the module backside, while voltage and current (V, I) for each module were measured at MPP and accordingly the power produced was calculated. The existing DAQ system of the STF was used for collecting and storing the measured data.

The experimental analysis showed that the PV module's peak temperature was shaved by 10 °C with the PCM effect compared to reference PV modules without PCM as shown in Figure 4. The experimental analysis confirmed the results of the numerical optimization, which revealed that there is an optimum thickness for PCM layer ~ 20-30 mm at 54 °C melting point. The analysis has revealed that cooling mechanism with heat fins alone (without PCM) achieved a temperature shaving of 5-8 °C.

Moreover, the module peak temperature can be shaved at a constant temperature for a longer time with higher PCM thickness of 50mm, as shown in Figure 5. The module temperature peaked at 54 °C during the noontime and remained at a temperature almost the same as the PCM melting temperature for five hours. Although the peak shaving effect with higher thickness of PCM is less than that of the optimum thickness of 30 mm, such thermal behavior with higher thickness of PCM can have a positive impact on stabilized power supply that is important for grid operation. In addition to that, three continuous days temperature profile is shown in Figure 6, which shows the continuous transient behavior and effectiveness of the PCM matrix absorber.

Energy yield is one of the most important parameters for assessing any new scheme or technology along with the expected lifetime for deploying that technology. In fact, those two parameters are what mostly concern the decision makers. Therefore, the monthly energy yield for the four tested modules is shown in Figure 7, where the PV module with 30 mm PCM attached to the back sheet shown the highest energy yield all along followed by the PV reference module, then the PV module with aluminum heat fins and finally the PV module with 50 mm PCM attached to the back sheet. As shown in Figure 7 the trend is almost stable and the difference in the total energy yield for each module per month due to the received irradiance only as the modules were cleaned three times per week.

In addition to that, for better comparison the cumulative energy yield for three months is shown in Figure 8. In fact, the PV module with 30 mm PCM attached to the back sheet shown a (2-5 %) higher energy yield compared to the PV reference module. Furthermore, the PV heat fins configuration shown a relatively lower energy yield compared to the reference module with 1.2% and the PV-PCM 50 mm configuration shown also a relatively lower energy yield compared to the reference module with 3%.

However, it is worth mentioning that a numerical simulation model has been developed in parallel, and validated against measurements under real operation conditions of PV modules in Qatar, to examine the effect of the PCM-Matrix Absorber (PCM-MA) on solar PV systems and optimize its properties for Qatar. For the optimized PCM-MA, which has been arrived at later after manufacturing the pilot plant, the PV module temperature is reduced by 23 °C, the energy yield can increase by 9-11% for mono and polycrystalline PV modules and 6-8% for thin film modules depending on the temperature coefficient of the high quality modules available in the international market. Presentation of the numerical simulation model and results will be elaborately discussed in a following publication.

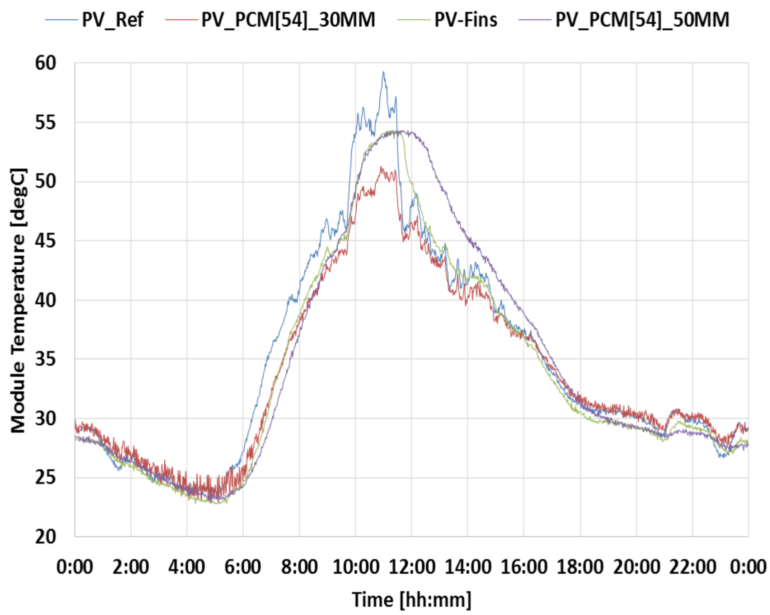

Figure 4: One-Day Temperature Profile 28th -Apr 2018

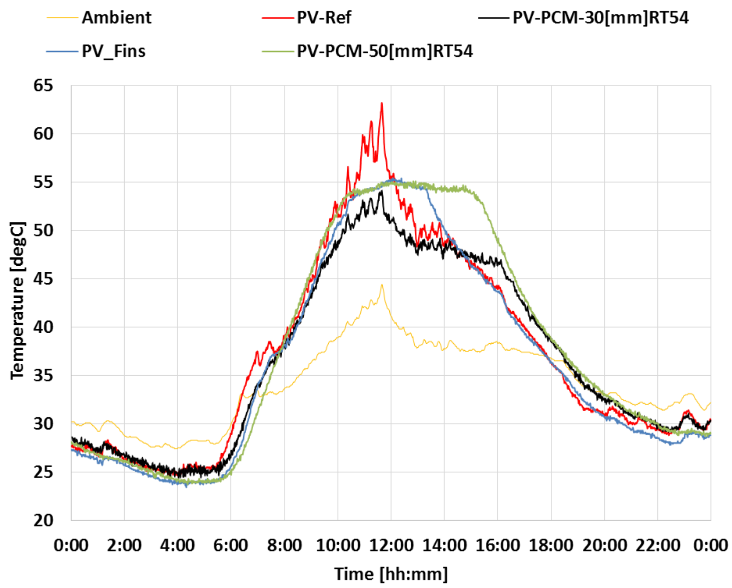

Figure 5: One-Day Temperature Profile 7th -May 2018

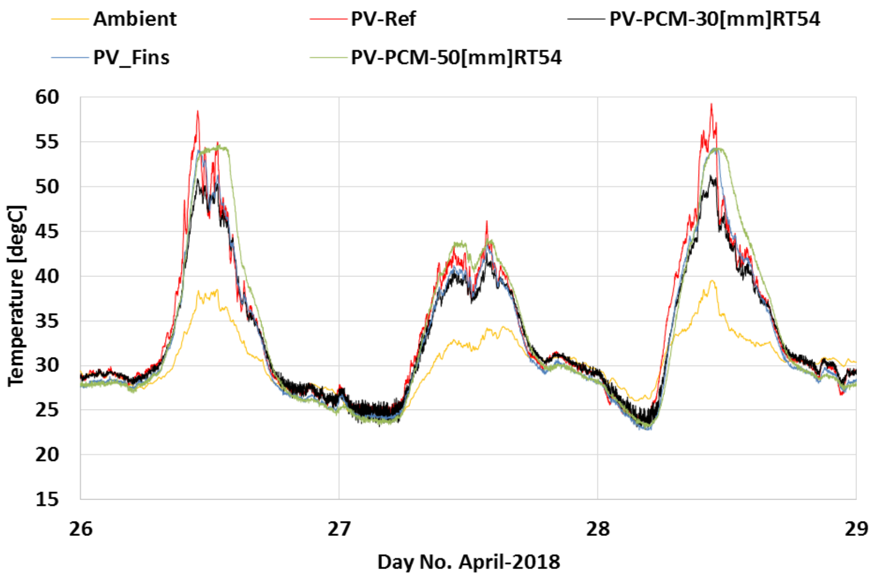

Figure 6: Three Days Temperature Profile 26th –To 29th Apr 2018

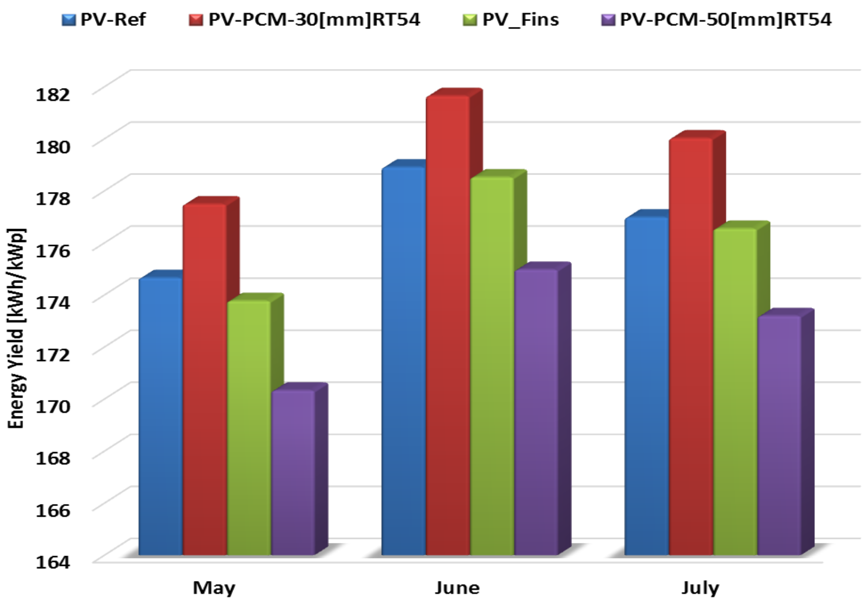

Figure 7: Monthly Energy Yield

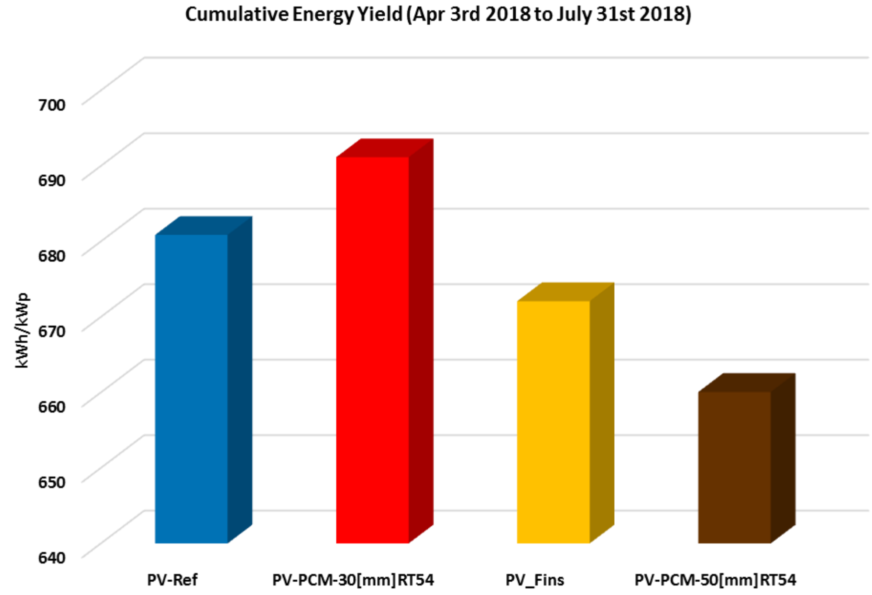

Figure 8: Cumulative Energy Yield

5. Conclusion

The efforts in this research focused on the development of a passive cooling of PV modules using phase change materials matrix absorbers for reliable operation of PV systems in deserts. The focus of this paper is on outdoor testing and experimental analysis to examine the effect of utilization of PCM based cooling elements incorporating cellular metallic heat conducting structures on the thermal behavior of solar PV panels.

Initially the passive cooling concept has been examined with one type of solar PV panels; Monocrystalline, with two thicknesses of PCM Absorber; 30 mm and 50 mm, melting point of 54°C and another arrangement with heat fins in place of the PCM layer, where both arrangements are compared with a reference PV module with no cooling devices attached to it. The experimental campaign has been conducted at the outdoor testing facility under weather conditions in Qatar for nine months from April to December 2018.

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6. Acknowledgment

The PCM-Matrix Absorbers and pilot plant has been manufactured and commissioned by the Fraunhofer-Institut für Fertigungstechnik und Angewandte Materialforschung (IFAM), Dresden, Germany. The great support of IFAM is gratefully acknowledged, and we thank the coauthors from IFAM who provided insight, efforts and expertise that greatly assisted the research.

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