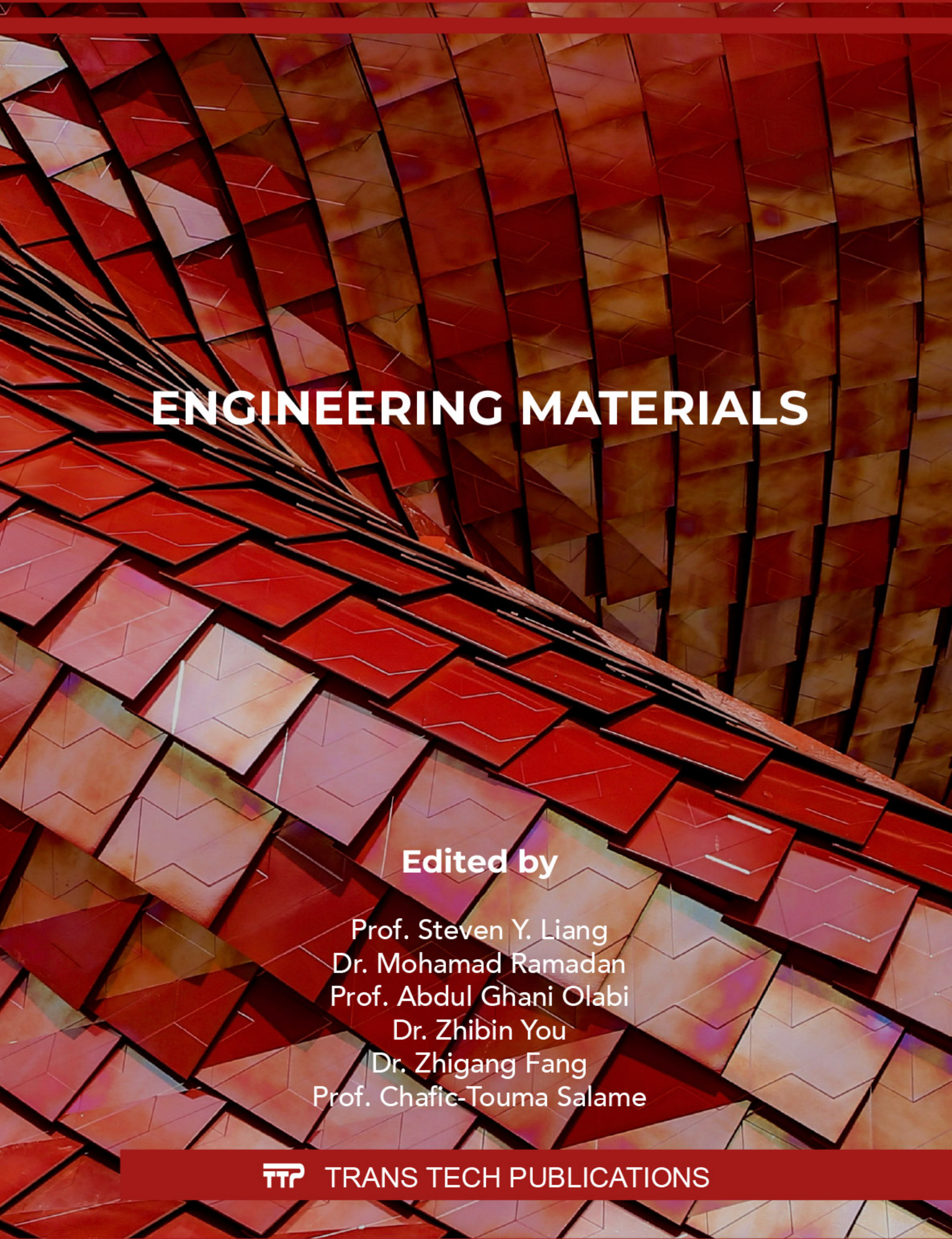

ENGINEERING MATERIALS

Edited by

Prof. Steven Y. Liang
Dr. Mohamad Ramadan
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Preface

The results of research and real engineering developments in the field of modern engineering materials are presented to readers in this issue.

Modern high-tech production is not complete without the use of special and highly functional materials. Phase change materials, shape memory materials, ceramics, energy storage materials, etc. significantly expand the functionality of finished products and equipment and increase the efficiency of their use.

All of the above can be fully attributed to materials that are widely used in the production of sensors, actuators and photovoltaic devices, without which the development of mechatronics, measuring technology and photovoltaics is impossible.

The study of the specifics of technologies for the processing of structural materials, the determination of optimal technological parameters and the selection of materials that meet technological requirements are today the basis for engineering preparation for production. In this edition, the reader will find some engineering solutions in this area.

Modern building materials using production waste and natural components, as well as wastewater treatment technologies based on photodegradation and photocatalytic treatment are important links in the sustainable development of modern technogenic society. Research results related to these technologies are also included in the publication.

This book will be helpful to specialists in materials science from many production branches.

Table of Contents

Chapter 5: Materials and Technologies for Environmental Engineering

CHAPTER 1:

Functional and Special Materials

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An Overview on the Use of Phase Change Material (PCM) for PV Cooling

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Keywords: Heat absorption, temperature effect, thermal management, phase change, PV cooling.

Abstract. The thermal management processes for PhotoVoltaic (PV) cooling applications, increase PV systems' overall efficiency and yield to a maximized power generation. Accordingly, this paper investigates recent PV thermal management methods, which involve the use of Phase Change Material (PCM) under the back of PV modules. Compared to other cooling methods (such as air and water based methods) PCM based techniques show less need for maintenance, are environment-friendly, and have a longer life cycle. Since PCM are diverse in nature, and many methods exist to guide their selection procedure, this paper begins by revealing different types of PCM, which are found to be as Organic, Inorganic, Eutectic and Commercial PCM, with the characteristics of each. After acknowledging different PCM natures, a selection process is established based on either the melting temperature, latent heat, or thermal conductivity of PCM. Results have shown that Commercial PCM are the best option followed by Organic PCM, due to their improved chemical aspects when compared with Inorganic and Eutectic PCM. Concerning PCM selection criteria, the easiest yet sufficient process is based on the melting temperature method, due to the simplified calculations when compared to other thermic quantities. At the end, future work recommendations are declared, related to PCM lifecycle assessment and cooling/heating cycles effects on PV entropy.

Introduction

Among various types of renewable energy supplies, PhotoVoltaic (PV) systems are top ranked, with most optimum efficiency and power generation capabilities. While possessing performance robustness, and ability to meet different load demands, PVs have a high future scope in power production [1]. The emission-less static operational mechanisms, omnipresent characteristics, and low maintenance costs [2], have popularized the adaption of such systems, with an elevated power productivity during a long life cycle.

In addition, solar irradiations are abundant where $1.2 \cdot 10^5$ TW of energy is continuously attaining earth's surface [3]. This fact has elevated the status of PV systems as a reliable and clean green energy supply. Accordingly, the usage of such systems would definitely contribute in reduction of global emissions, hence stabilizing climate change and global warming. Such granted advantages have globally evolved the market share of PV industry and increased different research topics of PV systems.

The PV power output can be maximized upon adaptation of certain optimization methods, since PV systems rely on unstable climatic conditions (i.e., irradiance, etc.) to produce power. This represents the new concern in PV research area. In other words, PV's outcomes are better exploited after installation of auxiliary sub-systems, such as Solar Trackers (ST) for example. An ST ensures that the maximum quantity of solar radiations hit the PV modules' surfaces in a perpendicular matter [4], hence producing more electrical power. From the same perspective, the monthly modification of

PV modules' tilt angle, have shown an increase in produced power, and a decrease in the levelized cost of energy [5].

From another part, PV Array Reconfiguration (PVAR) methods would equalize the generated PV string currents, hence compensating the negative effects of Partial Shading Conditions (PSC), which are caused by unavoidable physical (moving or static) light barriers [6].

When PV faults are accurately categorized and detected via PV Fault Diagnostic Tools (PV-FDT), further complications are prevented, such as partial/complete blackouts. This in turn would ensure a maximum power productivity with an increased PV system's lifecycle [7].

Apart of the importance of applying ST, PVAR, and PV-FDT as additional systems on a PV network, a proper PV modules' thermal management scheme is a key factor in elevating the overall system's efficiency, referred to as PV cooling methods [8]. Since the reduction of PV module's temperature (T_{PV}) would greatly enhance the generated power output of PV systems, cooling processes began by water and air based thermal removers [9]. The water-based cooling methods include water spraying, and usage of water nozzles on PV modules surfaces, but such methods deplete ground water which is considered the most vital human need. Instead, immersing the modules into water would reduce such losses, but in turn is not applicable in arid regions.

On the other hand, air-based cooling techniques also play a critical role in T_{PV} reduction, while not adding any additional equipment weights onto the PV system, as in the case of water-based methods. From another side, such cooling methods impose the need of ducts and other installations to conduct a proper airflow, which increases the overall cost of the system [10]. Aside from the previous PV thermal management strategies, heat sink coolers reduce T_{PV} effectively [11], with less maintenance costs, but would only properly operate when the wind speed is high.

Apart from the mentioned cooling methods, the usage of Phase Change Material (PCM) is the best remedial alternative. In this paper, an in-depth overview of various PCM types is conducted after a graphical representation of temperature effect over PV power output. Progressively, an investigation of the selection procedure of a PCM takes place, followed by a descriptive section revealing the effects of PCM application in PV systems. Finally, conclusions and future recommendations are exposed.

Temperature effect on PV output

PV systems' operations are highly affected by irradiation and ambient temperature. An inverse relation condemns the behavior of these systems, where any increase in temperature decreases a PV module's power generation, as seen in Fig. 1, based on the PV's mathematical model [12]. They also suffer from a low light-to-electricity conversion efficiency and dissipate large quantities of potential energy in form of heat.

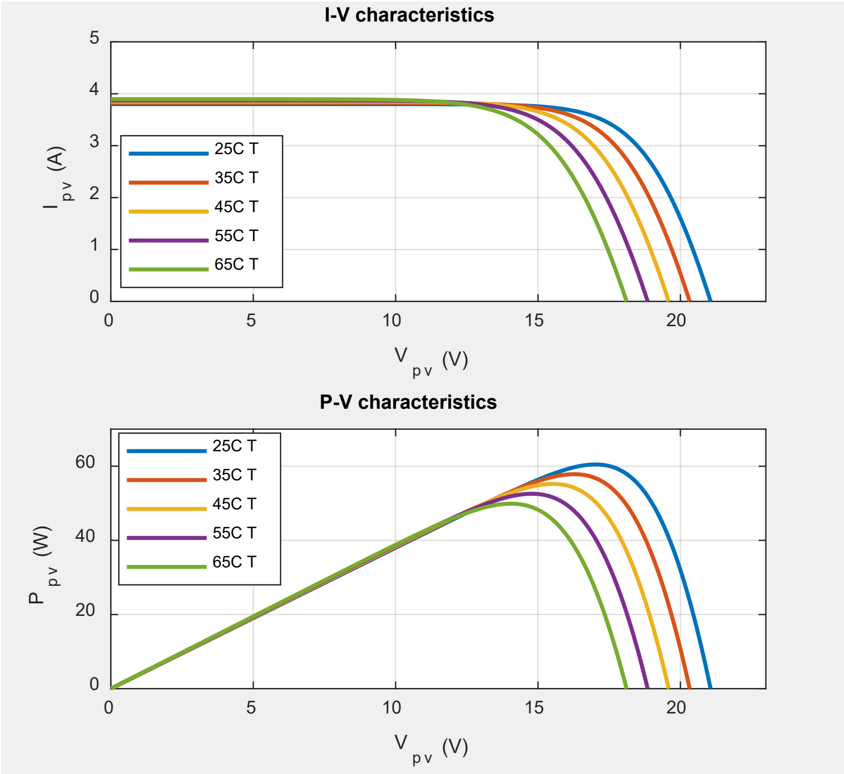

Fig. 1. Temperature effect over PV characteristic curves

It can be clearly deduced from Fig. 1 that an increase of 10℃ in temperature would decrease the output power by 2 W. Accordingly, a temperature of 65℃ would reflect an output power of 50 W, decreased by 10 W from the Standard Test Conditions (STC) temperature of 25℃ [12]. Therefore, cooling down T_{PV} has a direct positive effect on PV's output power, in parallel with other optimization techniques, such as Maximum Power Point Tracking (MPPT) [12], and PV cell raw materials designs [13].

Overview of different Phase Change Material (PCM)

A PCM is a physical entity that is able to absorb and release large amount of latent heat, during its phase transition (from solid-solid, solid-liquid, solid-gas, etc.). Between various physical properties transformations, solid-liquid transition type is the center of interest for PV module cooling process [14]. The PCM attains three distinct phases during the charging/discharging cycle. It first stores energy in form of sensible heat, of the solid phase PCM ($C_{P,s}$) until the material attains its melting temperature (T_{melt}). Afterwards, the PCM melts, consuming a thermal energy equivalent to the latent heat of fusion (H_m). In the last stage, the molten PCM absorbs the sensible heat in liquid phase PCM ($C_{p,l}$) [15]. The different types of PCM are shown in Fig. 2.

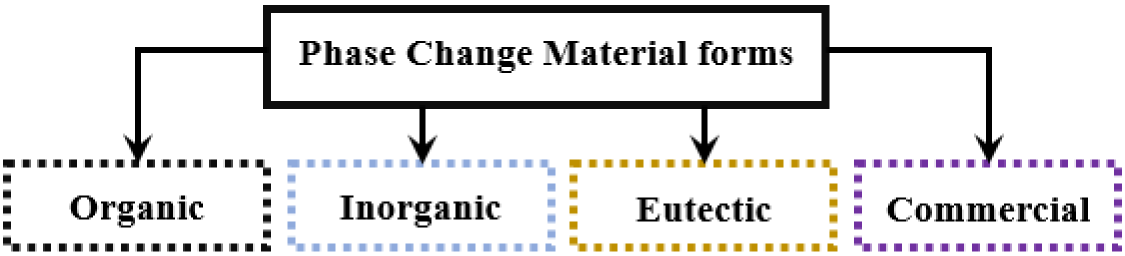

Fig. 2. Different types of PCM

Organic PCM are either Paraffin wax or fatty acids type (Capric acid, Lauric acid, coconut oil, petroleum jelly, etc.). Paraffin compounds can in turn have various natures, but they all share in common the saturated hydrocarbon (C_nH_{2n+2}) in essence, combined with other hydrocarbon chains. Such compounds offer an acceptable thermal stability, favorably to work for low-temperature applications [16]. Fatty acids PCM on the other hand, are still limited in PV cooling applications, mainly due to their low T_{melt} and low H_m.

Inorganic PCM are salt hydrate based, which contain higher H_m, density, and thermal conductivity when compared to Organic PCM. But still, the salt content, and its chemical instability pose a problem over a sustained PV module functioning [17], that is why Organic PCM are more preferred for PV cooling applications. The combination and hybridization between Organic and Inorganic PCM would result in a Eutectic PCM which overcome the issue of chemical degradation of individual Organic/Inorganic PCM. Eutectic PCM offer better flexibility in tuning T_{melt} but are more expensive than Organic PCM [18]. Hereafter, Eutectic mixtures result in Commercial PCM, which have longer thermally stable operations, possess a sharp T_{melt} as well as a high H_m, and present no super-cooling effects on PV modules. Although Commercial PCM reduce T_{PV} significantly, they are considered too expensive to install [19]. Table 1 encapsulates the differences between various PCM.

Table 1. Major differences between PCM types

PCM type	T_{melt}	Supercooling effect	Thermal conductivity	Cost
Organic	25°C *to* 60°C	Low	Low	Very low
Inorganic	30°C *to* 40°C	Moderate	High	Low
Eutectic	22°C *to* 23°C	Low	Moderate	Moderate
Commercial	10°C *to* 60°C	Low	Low	Very high

Selection criteria for different PCM

Concerning the various types of PCM, their selection process can be challenging. The PCM diversity, in terms of thermodynamic, kinetic, chemical, and financial standards, offer different selection processes intended for PV cooling, as summarized in Fig. 3.

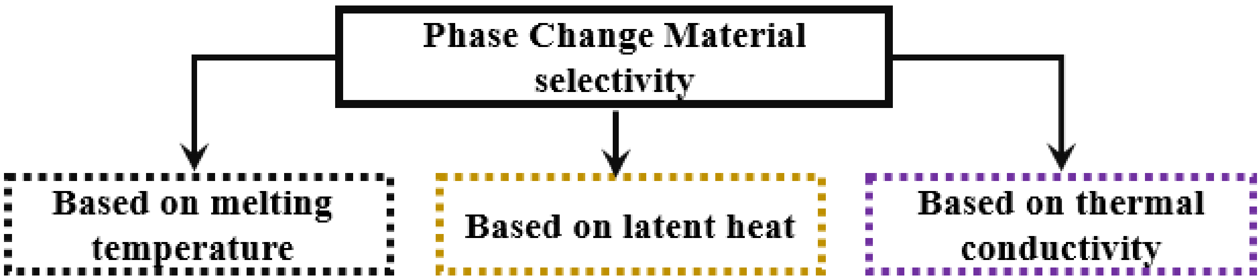

Fig. 3. Selection criteria of PCM

For isothermal heat removal, the selection of PCM based on T_{melt} is of crucial importance. In this case, the climatic conditions in the geographical region, at which the PV system is installed, governs the selectivity, as shown in Eq. (1) [20].

$$T_{PV} = T_a + \left(\frac{\tau\alpha}{U_{L0} + U_{L1}v}\right) G \tag{1}$$

with T_{PV}, T_a , $\tau\alpha$ representing the PV panel temperature, ambient temperature, and transmittance respectively, U_{L0}, U_{L1}, denoting the heat loss coefficients and v, G indicating the wind speed and irradiance respectively.

As a result from Eq. (1), the acknowledgment of T_{PV} would give a discrete option upon selecting an optimum T_{melt}. From another side, and since the latent heat is another characteristic of a PCM, the selection process can be based upon. The thermal regulation of an elevated T_{PV} depends on the PCM volume and its latent heat value. In other words, higher latent heat, provides longer thermal regulation. This process is mainly dependent on solar irradiance patterns, rather than ambient temperature conditions as in the previous criteria [21].

Lastly, the choice of PCM can be based upon material heat transfer. As indicated in Table 1, the majority of PCM have a low thermal conductivity, but for PV cooling aim, a high thermal conductivity is needed. Accordingly, this conductivity can be enhanced and thus the choice of a PCM can be based upon enhancement techniques. Some of these techniques include the addition of fins [22], and nanoparticles [23] to the heat sinks, what reflects as better energy storage of PCM. The choice in this case is based on the technique involved to enhance the thermal conductivity by auxiliary procedures.

Discussion

Aside from acknowledging different structures of PCM, as well as their selection processes, more data should be extracted from real world applications of PCM-cooled PV systems and investigated in order to truly determine what PCM type is most suitable for which PV application.

In other words, it is never sufficient to choose a PCM based on its most optimum thermal characteristics only. Despite the linear drop of PV cell efficiency by 0.45% for each temperature rise of 1℃ from PV's manufacturers datasheets [24], all of kinetic, chemical, technical, and economical criteria must be also taken into consideration in the selection process. This must take place in parallel with historical data information of actual PV networks, cooled via PCM. For this purpose, and as an example, Table 2 encloses different PV module temperature profiles, with/without usage of certain PCM.

Table 2. Thermal regulation effects for different PCM [24]

PCM type		T_{PV} before usage	T_{PV} after usage	T_{PV} reduction
Organic	Paraffin 46	55℃	45℃	10℃
	Octadecane	55℃	32℃	23℃
Inorganic	$Na_2SO_4.10H_2O$	45℃	35℃	10℃
	$Na_2HPO_4.12H_2O$	45℃	38℃	7℃
Eutectic	$CaCl_2.6H_2O$	60℃	38℃	22℃
	Capric:palmitic	60℃	50℃	10℃
Commercial	RT50HC	78℃	65℃	13℃
	RT54HC	78℃	62℃	16℃

As shown in Table 2, the varieties of PCM within the same set, could contribute differently to PV thermal management. For instance, concerning the Inorganic PCM set, the non-Paraffin compound (Octadecane) has better reduced T_{PV} in comparison with Paraffin 46, by 13°C. In some cases the T_{PV} reduction between mutual varieties is less, such as by 3°C, like in the case of using two different Inorganic PCM.

The important to notice is that not necessarily a set of PCM could better replace another, just because it had scored better temperature reduction for a PV module. Being said, since the T_{PV} tested with Organic PCM is higher than T_{PV} under Inorganic PCM study, that does not mean that Organic PCM would contribute better in lowering T_{PV} when subjected to the same environmental conditions, as in Inorganic PCM test scenario.