USE OF PHASE CHANGE MATERIALS IN PHOTOVOLTAIC MODULES WITH SOLAR CONCENTRATION UP TO 2X

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ABSTRACT: Module efficiency depends of the irradiance level and its temperature. Module temperature depends of ambient temperature, irradiance, thermal characteristic of the module, surrounding of the module, and the direction and wind speed. A silicon photovoltaic module improves its efficiency when decreasing its temperature about 0,5%/K.

The purpose of this paper is to analyze the possibilities of using phase change materials PCM, to limit the temperature of photovoltaic modules without concentration and with concentration up to 2X and thus increase its performance. We carry out a theoretical study that discusses this potential improvement in different climatic zones characterized by 12 sites. The results show that the use of PCM is a technically feasible alternative to limit the temperature of a photovoltaic module in some climates.

Keywords: PV module, thermal performance, PCM materials.

1 INTRODUCTION

Photovoltaic modules are always installed outdoor and when they are working the energy balance indicates that about 75-80% of the total incident energy is dissipated in heat, about 4-8% is reflected and about 7%-16% is transformed is electric energy. Therefore, in daylight the module gets a temperature in equilibrium with its ambient and the difference between module temperature and ambient temperature is about -5-55 K, depending strongly on the way the PV module is mounted (open rack, ventilated or unventilated roof mounting, etc.), wind speed and also on the module type [Palyvos, J.A., [1], Jurij Kurnik,[2]] when there is not solar concentration. If there is solar concentration, the difference between module temperature and ambient temperature are higher. In the other hand is known that module maximum power is reduced by increasing temperature in about 0,5%/K in crystalline silicon modules [Raziemska, 2003] [3].

The possibility of reducing the temperature using procedures based on cooling module by energy-consuming equipment is usually discarded because of their lack of economic and energetic viability. In contrast, it is advisable to expose the back side of the module to the wind in order to reach the lowest possible temperature. When exposed to the wind, convective energy exchanges are stimulated and therefore the temperature decreases.

Another alternative proposed in this paper is the use of phase change materials to limit the maximum temperature of the module changing the phase of the PCM from solid to solid-liquid without reaching the area of super cooled liquid. This is possible because the process is reversed at night from solid-liquid to solid. [Anica Trp, 2005, [4], M. Veerappan et al,[5]].

However, due to the variety of weather conditions, this application might only make sense in certain locations where module temperatures notable exceeds the ambient temperature (climates with high levels of radiation) and depending on the technical and economic features of the PCM.

It should be noted that when integrated photovoltaic module used in building other synergies could be raised to improve the benefits of using of using PCM. [Helmut Weinlader et al, 2005][6]. For example, the use of PCM would not only limit the temperature of the module but could be used simultaneously to stabilize the temperature inside the building between certain comfort values.

Other technical advantages of using PCM in photovoltaic modules that could be used would be standard commercial modules for use also with systems of low concentration of solar radiation. Currently can not be used as the manufacturers state not to exceed a maximum operating temperature of 358 K. If the photovoltaic system is subjected to a concentration of solar radiation on it, the maximum temperature reached is logically dependent on the concentration. For concentrations below of 2X, temperature can exceed 393 K. In this case, the use of PCM could limit this value to about 358 K, allowing the use of standards commercial modules in low concentrations.

2 OBJETIVE

The purpose of the work is to analyze the use of PCMs to limit the photovoltaic module temperature in a passive way, specifically in solar concentration systems up to 2X and to extend the results to different climatic conditions represented by 12 sites of the world.

The use of PCMs to limit the photovoltaic module temperature in a passive way has been analysed and experimentally proven by different authors [A. Hasan et all, 2010; [7] , M.J. Huang et all 2006 [8]. In this work we present the analysis of this application of PCMs to low concentration (up to 2X) PV systems. The performance of PCM-cooled modules has been compared to know the maximum energy use limits of the PCM depending on the weather and the role of assumptions made in the work. This study has been extended to 12 sites located in different locations with different climatic conditions.

3 HYPOTESIS AND METHODOLOGY

3.1 Hypothesis

We have considered the following hypotheses:

- <u>PCM Features:</u>

Calculations have been performed for a PCM phase change temperature of 298,15K ; 308,15K; 318,15 K and 328,15 K.

In the calculation of the minimum required PCM mass it is assumed an infinite thermal conductivity, a thermal packaging insulated from the environment and a phase change enthalpy of 200 kJ/kg and the PCM needed for the PV module temperature never exceeds the phase change.

Were have not been taken into account the effects of thermal stability, corrosion, toxicity, costs, etc… of the PCM.

<u>- PV module features</u>

Table I: Module Characteristics

PV MODULE CHARACTERÍSTICS	
Physical	Monocrystalline silicon
Dimensions	1310 x 969 x 39,5 mm
TONC (800W/m^2, 20ºC, AM 1.5, 1 m/s)	47º C
Emissivity(ε)	0.9
Electric (1000 W/m^2, 25ºC cell, Am 1.5)	
Maximum power ($P_{\text{máx}}$)	159 W_p ± 5%
Short circuit (I_{cc})	9,81 A
Open circuit voltage (V_{ca})	21,6 V
Maximum power current ($I_{\text{máx}}$)	9,15 A
Maximum power voltage ($V_{\text{máx}}$)	17,4 V
Performance (η_p)	0,125
Temperature parameters	
CCT I_{SC}	0.0294 %/K
CCT V_{OC}	-0.387 %/K
CCT P_{max}	-0.48 %/K

The PV module is installed supposing conditions of free movement of air though the back side (ω =1) inclined at the same latitude than the location, facing the Equator.

In the case of using PCM it is considered that the photovoltaic module will always be at the phase change temperature of the PCM.

3.2 Methodology

The proposed methodology has been performed both for a PV module without concentration and a PV module with solar radiation concentration of 2X. The 12 considered sites are:

Table 1: Geographical location of the different cities under study.

CITY	COUNTRY	LATITUDE (º)	LONGITUDE *(º)
Seville	Spain	37.72	-5.58
Paris	France	49.12	2.09
London	United Kingdom	51.35	0.02
Helsinki	Finland	60.19	24.58
New York	United States	40.46	-73.54
San Salvador	El Salvador	13.42	-89.07
Buenos Aires	Argentina	-34.35	-58.29
Río de Janeiro	Brazil	-22.55	-43.10
Cairo	Egypt	30.05	31.17
Nairobi	Kenya	-1.18	36.45
Cape Town	South Africa	-33.58	18.36
Sidney	Australia	-33.52	151.12

(*) Positive longitude values at the east

For each of the 4 levels of phase change temperature (298,15K, 308,15K, 318,15K and 328,15 K) has been determined:

- Maximum daily time while the module temperature would be limited by the PCM until its phase change temperature, te (h).
- Energy that should absorb the PCM so that the module temperature does not exceed the phase change temperature of the PCM. Ev (kJ/m2)
- PCM minimum mass required. mPCM (kg/m2).
- Percentage increase of produced energy by the photovoltaic modules per year and per area unit by incorporating the PCM in respect of non-use of PCM. ΔE (%/m2).

Maximum daily time while module temperature would be limited to the phase change temperature, Te (h)

To determine Te, for the 4 phase change temperature, (298,15 K, 308,15 K, 318,15 K y 328,15 K) it has been disposed the hourly temperature over the year of the PV module according to the weather conditions provided by the climate database Meteonorm V.4.0.

Subsequently it has been determined Te_i hours, when the module temperature is above the phase change temperature, Tc. The sum for the entire year leads to Te(h). The variables that have been used are:

- Annual hourly tilted radiation (Wh/m2) (with the same inclination as the latitude of the site and facing the equator).
- Annual hourly ambient temperature (ºC).
- Annual hourly wind speed (m/s).
- Annual hourly sky temperature (ºC).

For each level of phase change temperature, T_{PCM}, the variable $T_{e,hm}(T_{PCM})$ is calculated as the time for each hour h, of the month m, such as:

$T_{e,hm}(T_{PCM}) = 1$ if $T_{p,hm} - T_{PCM} > 0$ with h =1—24 h.

$$T_{e,m}(T_{PCM}) = \sum_{h=1}^{h=24} T_{e,hm}(T_{PCM}) \qquad 3.1$$

$T_e(T_{PCM}) = \max(Te_{,m}(T_{PCM}))$, with m= 1—12

Where the monthly average hourly temperature of the photovoltaic module T_{phm} is determined by the expression [1].

$$T_{p,hm} = T_{a,hm} + \omega \cdot \left(\frac{0.32}{8.91 + 2.0V_{v,hm}} \right) \cdot I_{hm} \qquad 3.2$$

Where:

$T_{p,hm}$: Hourly monthly average temperature of the PV module (ºC)
$T_{a,hm}$: Hourly monthly average ambient temperature (ºC)
$V_{v,hm}$: Hourly monthly average wind speed (m/s)
I_{hm}: Hourly monthly average global irradiation (W/m^2)
ω: Assembly coefficient (Free standing ω =1).

Hourly monthly, daily monthly and yearly average electric energy at the output of the module without PCM ($E_{e,hm}$, $E_{e,dm}$, E_e)

The hourly monthly average electric energy generated by the PV module without PCM is measured in Wh/m2 and is given by the expression:

$$E_{e,hm} = \int P_{e,hm}\,dt \qquad 3.3$$

Where P_{ehm} is the average electrical power in each hour "h" of the month "m" generated by the PV module without PCM and is given by the expression 3.4:

$$P_{e,hm} = \eta_p I_{hm} \left[1 - \beta_{ref} \left(T_{a,hm} + \omega \frac{0.32}{8.91 + 2.0V_{v,hm}} I_{hm} - 25 \right) \right] \qquad 3.4$$

Where:

P_e: Hourly monthly average electrical power at the output of the PV module without PCM (W/m^2).
η_p: Performance of the photovoltaic module (=0,125)
I_{hm}: Hourly monthly average global inclined irradiance (W/m^2)
$T_{a,hm}$: Hourly monthly average ambient temperature (ºC)
ω: Assembly coefficient (=1)
$V_{v,hm}$: Hourly monthly average wind speed (m/s)
β_{ref}: Coefficient of module efficiency correction by temperature given by the module manufacturer (= -0.48 %/K)

To calculate the hourly monthly average electricity generated by the PV module without PCM , equation 3.5 is used:

$$E_{e,dm} = \sum_{h=1}^{h=24} E_{e,hm} \qquad 3.5$$

To calculate yearly average electricity generated by the PV module without PCM, we use the equation 3.6:

$$E_e = \sum_{m=1}^{m=12} E_{e,dm} \cdot n_m \qquad 3.6$$

Where:

n_m: Number of days of the month "m"

The hourly monthly net average electricity, the daily monthly net average electricity and the yearly net average electricity at the output of the PV module with PCM ($E_{e,hm}^{PCM}$, $E_{e,dm}^{PCM}$ y E_e^{PCM}).

The hourly monthly net average electricity at the output of the PV module with PCM is measured in Wh/m^2 and is given by expression 3.7

$$E_{e,hm}^{PCM} = \int P_{e,hm}^{PCM}\,dt \qquad 3.7$$

Where P_{ehm}^{PCM} is the average electrical power in each hour "h" of the month "m" generated by the PV module with PCM and is given by the expression 3.8:

$$P_{e,hm}^{PCM} = \eta_p I_{hm} \left[1 - \beta_{ref} \left(T_k - 25 \right) \right] = \eta_p I_{hm} \qquad 3.8$$

Where:

$P_{e,hm}^{PCM}$: Hourly monthly average electrical power at the output of the PV module with PCM (W/m^2).
η_p: Performance of the module
I_{hm}: Hourly monthly average global inclined irradiance (W/m^2)
T_{PCM}= Phase change temperature (ºC)

The calculation of the daily monthly average electricity generated by the photovoltaic module with PCM is given by the equation 3.9:

$$E_{e,dm}^{PCM} = \sum_{h=1}^{h=24} E_{e,hm}^{PCM} \qquad 3.9$$

The yearly net average electricity at the output of the Pv module with PCM is obtained from the equation 3.10:

$$E_e^{PCM} = \sum_{m=1}^{m=12} E_{e,dm}^{PCM} \cdot n_m \qquad 3.10$$

The calculation of the annual increase of electrical energy by the use of PCM is obtained from

$$EP = \sum_{m=1}^{m=12} \sum_{h=1}^{h=24} (E_{e,hm}^{PCM} - E_{e,hm}) \qquad 3.11$$

Daily monthly average mass of PCM per unit area ($M_{pcm,dm}$) and the minimum required PCM mass per unit area (M_{pcm})

Both are measured in (kg/m2), and the daily monthly average mass of PCM per unit area is calculated by the equation 3.12:

$$M_{pcm,dm} = \frac{E_{v,dm}}{\Delta H / 3600} \qquad 3.12$$

Where:

ΔH: Phase change enthalpy

The minimum required PCM mass per unit area is equivalent to the most adverse month for the equation of thermal energy from the photovoltaic module. Can then be defined, required mass of PCM per unit area (M_{pcm}) using the expression 3.13:

$$M_{pcm} = \max\left(M_{pcm,dm}\right) \qquad 3.13$$

Where:

$P_{i,hm}$: Irradiancia global inclinada media horaria mensual (W/m^2)

Hourly Monthly average of maximum thermal energy, daily Monthly average of maximum thermal energy and annual average of maximum thermal energy available in constructions ($E_{v,hm}$, $E_{v,m}$ and E_v).

Hourly Monthly average of maximum thermal energy available in constructions is measured in Wh/m2 and is given by the equation 3.14:

$$E_{v,hm} = I_{hm} - E_{i,hm} \qquad 3.14$$

Where:

I_{hm}: Hourly monthly average global inclined radiation (Wh/m^2)
E_i: Hourly monthly average of incident energy on the PV module, required to not exceed the set temperature (Wh/m^2), is given by the next equation:

$$E_{i,hm} = \int P_{i,hm}\,dt \qquad 3.15$$

Where:

$P_{i,hm}$: Hourly monthly average global inclined irradiation on the PV module, required to not exceed the set temperature. To calculate this, we appeal to the expression 3.16:

$$T_{p,hm} = \frac{P_{i,hm}/2 + \left(2.8 + 3.0V_{v,hm} + 0.93h_{rd,hm}\right)\cdot T_{a,hm}}{2.8 + 3.0V_{v,hm} + h_{rd,hm}} \qquad 3.16$$

In the equation above appears the hourly monthly average radiation coefficient $h_{rd,hm}$ that is given by the next equation:

$$h_{rd,hm} = 4\cdot\sigma\cdot\varepsilon_p\cdot\left(\frac{T_{p,hm} + T_{c,hm}}{2}\right)^3 \qquad 3.17$$

Where:

V_{vhm}: Hourly monthly average wind speed (m/s)
T_{phm}: Hourly monthly average temperature of the PV module (K)
$T_{c,hm}$: Hourly monthly average sky temperature (K)
T_{ahm}: Hourly monthly average ambient temperature (K)
$h_{rd,hm}$: Hourly monthly average radiation coefficient on the PV module (W/m^{2}K)
σ: Stefan-Boltzmann constant (5.67e-8 W/m2K4)
ε_p: Emissivity of the PV module.

This energy corresponds to the monthly average hourly energy necessary to evacuate the photovoltaic module under climatic conditions for it to remain at the set temperature.

To calculate the daily monthly average of maximum thermal energy available for constructions, we use the equation 3.18:

$$E_{v,dm} = \sum_{h=1}^{h=24} E_{v,hm} \qquad 3.18$$

To calculate the yearly average of maximum thermal energy available for constructions, we use the equation 3.19:

$$E_v = \sum_{m=1}^{m=12} E_{v,dm}\cdot n_m \qquad 3.19$$

The Ev values obtained represent the annual average of maximum energy that once evacuated from the photovoltaic module may be used in constructions. That is, the primary source of thermal energy which is available to start the second application of this project:

4 RESULTS

4.1 Time necessary to limit annual temperature in the module.

PV modules without concentration:

The following graph shows the number of hours per year that the limitation of the PV module temperature is necessary depending on the melting temperature of the PCM, Tc, and the location of the installation:

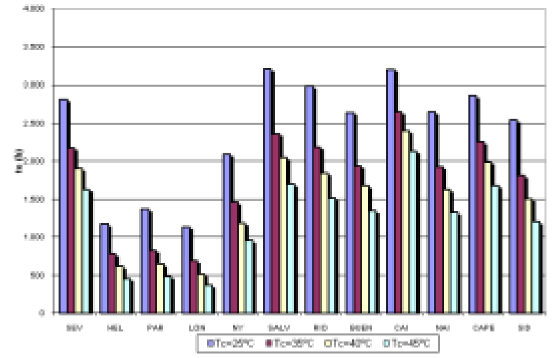

Figure 1: Annual necessary temperature limitation time for PV modules without solar concentration.

Number of hours Te depends on Tc which extreme values go from 3200 h in EL Cairo to 1137 h in London. For Tc=45ºC, Te values are 2134 h in El Cairo and 367 h in London.

PV modules with concentration of 2X:

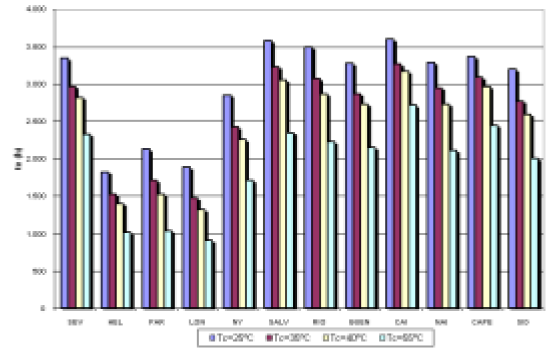

Figure. 2: Annual necessary temperature limitation time for PV modules with concentration of 2X.

In this case, number of hours Te depends on Tc. For a Tc value of 25ºC, extreme values increase from the case without solar concentration: 3603 h in Cairo to 1886 h in London. For Tc = 45ºC, Te values are 2718h in Cairo and 916 h in London.

4.2 Comparison between the energy generated (E.P., kWh/m^2 annual) and its increase percentage (ΔE, %).

PV modules without concentration:

At this point, we compare the energy generated (E.P., kWh/m^2 annual) with its increase percentage (ΔE, %) at the 12 locations selected in this work for two extreme melting temperatures of 25ºC and 45ºC.

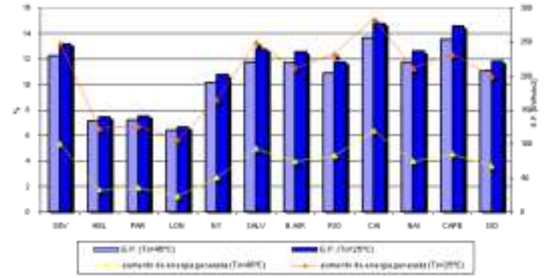

Figure 3: Comparison between E.P. (kWh/m^2 annual) and ΔE (%)for Tc=25, 45ºC.

As the melting temperature increases, both the increase of generated energy and its value, reduce. Moreover, we also observe that in the case when melting temperature is 45ºC, the differences between energy percentage increases between the different selected sites are not so extreme as in the case of 25ºC because when the set temperature is 45 ºC, the module is not subjected to a limitation in temperature as pronounced as in the case of 25ºC.

PV modules with concentration of 2X:

In first place, we compare the annual generated energy by the PV module (E.P. kWh/m^2 year) in each city without restrictions of temperature and after a PCM limitation such that the melting temperature is between 25ºC and 45ºC. It is also represented in the next graph the percentage increase of the generated energy (ΔE, %).

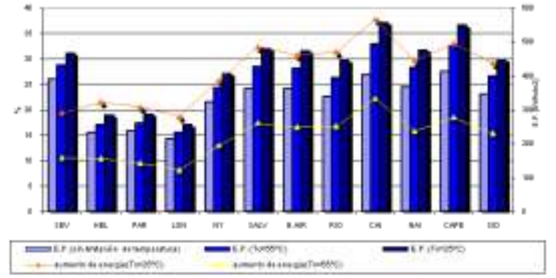

Figure 4: Comparison between E.P. (kWh/m^2 annual) and ΔE (%) for Tc=sin, 25 ºC and 45 ºC

As shown, the photovoltaic module that generates more energy in the case of concentration is located in Cape Town, (412.13 kWh/m^2), followed closely by the one installed in Cairo (403.71 kWh/m^2).

Moreover, the city with the lowest production is London (214.98 kWh/m^2), a value that can grow to the amount of 232.69 and 255.27 kWh/m^2 for a melting temperature of 25ºC and 45ºC respectively.

The values above assume that he largest percentage increase of energy is given in Cairo (22.25 and 37.82% for temperature melting of 45 and 25°C), whereas, the smaller percentage increase is given again in London (8.23 and 18.74% respectively).

It is also noteworthy the fact that although the city of Seville is one of the most productive (390.63; 432.05 and 466.48 kWh/m^2) its percentage increases in energy are very small in this case (10.6% and 19.42%).

4.3 Maximum necessary PCM mass to incorporate (kg/m2) and ΔE (%) for cases with/without concentration and Tc= 25ºC.

The PCM necessary mass is shown in the next W graph for a melting temperature of 25°C

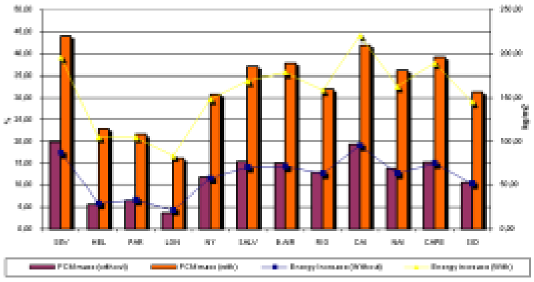

Figure 4: Comparison of the necessary PCM mass (kg/m^2) for the cases with/without concentration and Tc=25ºC.

5 CONCLUSIONS

- It has been quantified the maximum possibilities of using PCM in PV modules depending on the location, for modules without concentration and with concentration of 2X
- It shows that the possibilities of PCM are closely linked to location of the installation and the possibiity of solar concentration. In the cities studied the results concluded are very different, like in the case of London and Cairo. With concentration of 2X, the increase of electric production in the module reaches a 37.2% in Cairo and an 18% in London falling to a 15.1% and a 5.6% respectively in the cases without solar concentration.
- PCM mass necessary to achieve increases in electricity production of the modules is significantly elevated. However, if you want to limit the module temperature values of 45 ºC, the amount of PCM material drops significantly
- It is necessary a further development of the properties of the PCM materials and match possibilities with building to be economically viable in its use in photovoltaic modules

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