



# Experimental study of phase change materials for photovoltaic modules: Energy performance and economic yield for the EPEX spot market



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## ABSTRACT

Cooling of photovoltaic (PV) devices increases voltage and power output, but in standard applications, cooling measures are only beneficial if the associated costs are lower than the cumulative profit. A technical and economic analysis of a passive cooling measure based on phase change materials (PCMs) is conducted here. Three PV modules, one standard reference module and two equipped with PCMs, are studied experimentally. Although both have the same melting temperature, one of the PCMs has a significantly higher thermal conductivity and a lower heat storage capacity than the other. The analysis of the present experimental data considers the energy price variation at the European Power Exchange (EPEX) spot market during the day without considering any costs. Because additional power is supplied before noon for PCM charging, favorable results are observed during this period. However, higher operating temperatures of the PV modules occur later in the day due to the thermal insulation effect of the PCM layer attached to the back side of the modules. In total, this results in a negative economic yield on most days. The PCM with a higher thermal conductivity had significantly lower temperatures after charging and a corresponding higher yield.

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## 1. Introduction

The negative effect of elevated operating temperatures on the conversion efficiency of crystalline silicon solar cells is well known (Radziemska, 2006). Interventions to reduce operating temperatures are usually considered to increase the electrical energy yield. Low operating temperatures of photovoltaic (PV) modules also have a positive effect on degradation (Meyer and van Dyk, 2004; Junsangsri and Lombardi, 2010). Furthermore, a damping of short-term temperature fluctuations may increase PV module lifetimes (Köntges et al., 2014).

Both active cooling measures, such as water cooling on the module back (Bahaidarah et al., 2013; Moharram et al., 2013) or front side (Krauter, 2004), and passive cooling measures adapted from latent heat storage consisting of selected phase change materials (PCMs) have been investigated (Norton et al., 2011; Hasan et al., 2014). The scientific interest in using PCM for the thermal management of PV modules has increased rapidly over the last decade. Numerous experimental and computational studies have

been conducted for the use of PCM to manage the temperature issues of electronic devices such as PV modules (Browne et al., 2015). Meanwhile, it is well known that the operating temperature of PV modules can be decreased significantly due to the melting of the attached PCM. However, at high temperatures, PCM layers may cause unwanted and significant thermal insulation due to their typically low thermal conductivity. One possibility of combating this problem is to mix the PCM with expanded graphite (Mehling and Cabeza, 2008).

The first investigation into integrating PCM with a PV module was conducted in 1978; this study showed that the beneficial cooling effect of PCM can be enhanced by increasing its thermal conductivity and increasing the heat transfer from the PV module to the PCM at the thermal interface (Stultz and Wen, 1977). Recently, one of the main research objectives of Huang et al. (2011) was to promote the heat transfer into and out of PCM using fins within the aluminum container encapsulation. They also developed a validated numerical model for a PV-PCM module. Hasan et al. (2015) compared the effects of two different PCMs encapsulated in an aluminum container with internal fins for two different climate conditions (Dublin, Ireland and Vehari, Pakistan) using outdoor measurements and simulations using the numerical model from Huang et al. (2011). Two main conclusions were drawn: First, the deviation between the simulation and experiment results was very

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## Nomenclature

### Symbols

$c_p$	average specific isobaric heat capacity (kJ/(kg K))
$E$	energy yield (W h)
$e$	relative energy yield difference (%)
$h$	specific enthalpy of fusion (20–30 °C) (kJ/kg)
$P$	electrical power output (W <sub>p</sub> )
$r$	energy price (€/kW h)
$t$	time (s)
$Y$	economic yield (€)
$y$	relative economic yield difference (%)
$\gamma$	temperature coefficient of $P_{max}$ (%/K)
$\eta$	conversion efficiency (%)
$\theta$	temperature (°C)
$\lambda$	thermal conductivity (W/(m K))
$\rho$	specific density (kg/m <sup>3</sup> )
$\omega$	mass fraction (g/g)
$\Delta$	difference

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$d$	based on a daily trading period
$eq$	equipped with PCM or PCM <sup>+</sup>
$i$	counting variable
$j$	15 min or 1 h time block energy price
$m$	melting point
$max$	maximum point
$n$	summation limit
$ref$	reference
$uq$	unequipped (no PCM or PCM <sup>+</sup> )

### Abbreviation

EPEX	European Power Exchange
ISFH	Institute for Solar Energy Research Hamelin
MPP	maximum power point
PV	photovoltaic
PCM	phase change material
PCM <sup>+</sup>	phase change material with improved thermal conductivity
STC	standard test conditions

low in terms of the average temperatures of the front surface of both PV-PCM modules. Second, the highest temperature drop was approximately 21 K compared to the reference PV module was observed in Vehari for a PV-PCM module based on a salt hydrate.

Laboratory experiments combined with a computational study were conducted by Jay et al. (2010). Two PV-PCM systems, a PV module with a thermally insulated back side and a reference PV module, were simultaneously exposed to three different insolation intensities (600, 800 and 1000 W/m<sup>2</sup>) using a solar simulator. Both paraffin-based PCMs (with melting temperatures of 27 °C and 45 °C) were filled into a honeycomb aluminum structure, which was closed on both sides by an aluminum plate to promote heat transfer from the PV module. A 15–25 % increase in energy yield compared to the reference PV module due to temperature regulation was measured.

The combination of PCM-infused graphite and finned heat sinks for the thermal management of PV modules (Atkin and Farid, 2015) achieved a 13% increase in energy yield through reduced peak temperatures and a temporary time shift in the temperature rise.

In the present work, a commercial paraffin RUBITHERM<sup>®</sup> RT 28 HC with an improved thermal conductivity of  $\lambda = 2.4$  W/(m K) and the same PCM compound with the standard thermal conductivity of  $\lambda = 0.19$  W/(m K) were studied. The high thermal conductivity was achieved by adding expanded graphite to the PCM compound. Although the improved PCM (hereafter referred to as PCM<sup>+</sup>) has a reduced heat storage capacity because of a decreased mass fraction of the effective phase change material, it promises better performance and applicability. Therefore, one PV module was equipped with PCM<sup>+</sup> and another PV module was equipped with the conventional PCM; both were compared with a standard reference PV module, simultaneously measured at outdoor summer conditions during the year 2013 in Paderborn, Germany. A technical comparison of the two PV-PCM modules was conducted to assess the temperature development and energy yield.

In general, due to the rapid decrease of PV module costs, cooling interventions are often less cost-effective in terms of direct power gain. On the other hand, the typical power generation shift to the morning hours with PV-PCM modules may nonetheless be favorable, considering the higher electricity prices before noon on the European Power Exchange (EPEX) spot market, cf. Fig. 1. In this

investigation, no costs were considered, and the economic analysis focused exclusively on the yield differences due to the use of PCM and PCM<sup>+</sup>.

## 2. Measurement setup

### 2.1. Characterization of PCM and PCM<sup>+</sup>

The applied PCM was hermetically encapsulated in bags consisting of an aluminum-polymer composite film with 500 g of PCM each. The thermal conductivity of the RUBITHERM<sup>®</sup> RT 28 HC alone was  $\lambda = 0.19$  W/(m K); this was significantly increased by adding expanded graphite (THERMOPHIT<sup>®</sup> GFG, SGL GROUP), following the work by Sonnenrein et al. (2015). After adding graphite with a mass fraction of  $\omega \approx 0.2$  g/g, the thermal conductivity of PCM<sup>+</sup> increased by more than a factor of 12. Therefore a thermal conductivity of  $\lambda = 2.4$  W/(m K) has been measured by applying the stationary method as described in Mehling et al. (2000). Fig. 2 shows the temperature dependence of the specific enthalpy of PCM<sup>+</sup> compared with that of pure PCM. The underlying measurements were conducted with heat flow 3-layer-calorimeter (WOTKA, W&A) (Kenfack and Bauer, 2014) specifically developed for analyzing PCM and for validation additionally with Differential Scanning Calorimetry (DSC, TG-DSC 111, SETARAM) (Sarwar and Mansoor, 2016). Compared to common DSC devices, WOTKA allows increased sample quantities of up to 100 g what is of particular importance to determine the phase change temperature of composites. Therefore, the study shows in the following the experimental results of the 3-layer-calorimeter measurements.

The heat storage capacity of the compounded material is lower than that of pure PCM due to its significant graphite content. Over the temperature range of 20–35 °C, the specific heat storage capacity was thus reduced by approximately 28%, from 260 kJ/kg to 185 kJ/kg. The melting temperature remained unaffected at approximately 28 °C. It should be noted that the paraffine used here shows no significant sub-cooling, unlike common salt hydrates. Based on the measured PCM properties, the amount of storable heat per PV module over the temperature range of 20–35 °C was approximately 391 kJ for PCM and approximately 275 kJ for PCM<sup>+</sup> (cf. Fig. 2 and Table 1).

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