Photovoltaic module temperature stabilization with the use of phase change materials

Ewa Klugmann-Radziemska Patrycja Wcisło-Kucharek

Gdansk University of Technology, Faculty of Chemistry, ul. Narutowicza 11/12, PL-80-233 Gdansk, Poland

a b s t r a c t

The worldwide growth of photovoltaics (PVs) has formed an exponential curve for more than four dec-ades. During this period of time, PVs have evolved from a pure niche market of small-scale applications towards becoming a mainstream electricity source. The influence of temperature on the electrical param-eters of crystalline silicon solar cells and solar modules is well described in the literature. In order to diminish these effects, it is useful to decrease the module temperature by removing the heat in a hybrid system that combines a PV module and thermal collector (T) into a photovoltaic–thermal (PV/T) system. Two types of PV/T systems are popular on the market: air cooled and water cooled. A relatively new solu-tion is the use of phase change material (PCM) in order to pick up excess heat. PCMs absorb, store, and release large amounts of energy in the form of latent heat at constant temperature. Many innovative applications can be found for PCMs, which raise the efficiency of equipment, among other advantages. In the present paper, the experience of using PCMs for the stabilization of PV module temperature is pre-sented. The results of these experiments are promising: for constant solar irradiance, the modified solar PV module (PV/PCM) heats up to a lower temperature than the unmodified PV module and the cheapest option is to apply 42–44 paraffin to the module without cooling, which made possible to lower the tem-perature of the module by 7 K. During the experiment, the lowered temperature was maintained for more than 5 h, allowing the PV module to work at a temperature close to the optimum one for the entire period of intense lighting.

Keywords: Photovoltaic module, Temperature stabilization, Phase change materials, Paraffin

1. Introduction

In order to increase the efficiency of photovoltaic (PV) modules, it is useful to decrease the module temperature by removing the heat in a hybrid system that combines the PV module and thermal collector (T) into a photovoltaic-thermal (PV/T) system.

The advantages of using a hybrid system, especially one inte-grated with the building, are (Leenders et al., 2000): reduced pro-duction costs of one hybrid compared to the use of two different collectors, reduced roof area, reduced installation and mounting costs of the system, enhanced uniform architectural appearance and aesthetics, reduced operation temperature (PV cell tempera-ture) and increased conversion efficiency as observed in the system described in Radziemska (2003).

The thermal efficiencies calculated from the theoretical model are about 55% for air-cooled systems and in the range of 45–65% for the water-cooled type (Sopian and et al., 1996; Bhargava et al., 1991).

The applications of phase change materials (PCMs) can be divided into two main groups: thermal protection or inertia and storage. The difference between these two substantial fields of applications relates to the thermal conductivity of the substance.

PCMs are proposed for use in PV modules to limit the cell tem-perature by absorbing heat during melting. Malvi et al. (2011) pre-sented a model and simulation results for a combined photovoltaic - solar thermal (PV/ST) system that incorporates PCM.

Huang et al. (2006) presented an experimental evaluation of PCMs for thermal management of PV devices. For three different PV/PCM systems, using RT25, the temperature at the front surface of the PV/PCM system was maintained below 29 °C for 130 min with insolation of 750 W/m^2 and an ambient temperature of 23 °C.

Hasan et al. (2010) achieved maximum temperature reductions of the PV front surface of 18 K for 30 min with the use of capric-palmic acid and $CaCl_2$ and 10 K for 5 h under irradiation of 1000 W/m^2 with the use of $CaCl_2$.

Huang (Huang et al., 2004) developed a numerical PV/PCM model and validated it successfully by comparison with experi-

Nomenclature

A	surface, m^2
C_p	heat capacity at constant pressure, kJ/K
c_p	specific heat at constant pressure, kJ/(kg K)
E	daily irradiation, W h/m^2 day
E_g	band gap, eV,
e	elementary charge, C
G	global irradiation on a plane, W/m^2
H	enthalpy, kJ
h	specific enthalpy, kJ/kg
I	electric current, A
k	Boltzmann's constant, J/K, calorimetric constant
P	electric power, W
Q	heat, J
R	electrical resistance, Ω
T	temperature, K
t	temperature, °C
V	voltage, V
x	thickness of layer, m

Greek symbols

α	silicon power temperature coefficient, %/K
β	silicon efficiency temperature coefficient, 1/K
η	efficiency of the module, %
λ	thermal conductivity of a material, W/(m·K)
ρ	mass density, kg/m^3
τ	time, h

Subscripts

0	at a temperature of 298 K
1	initial
2	final
amb	ambient
m	melting
oc	open cell
opt	optimum
sc	short circuit

ments. At insolation of 1000 W/m^2 and an ambient temperature of 20 °C, for a system with two fins using PCM with a melting temperature of 32 °C and depth of 20 mm, the temperature on the front surface was maintained below 36.4 °C for 80 min.

Gkouskos et al. announced their intention to perform several experiments in the future by varying the type of PCM and its thickness in order to investigate the effect of the thickness of the PCM layer (RT27) on the energy conversion efficiency of the system and to find the optimal PCM for the weather conditions of a typical Mediterranean region (Gkouskos et al., 2012).

Cellura et al. presented the results of a numerical simulation of the thermal behaviour of an integrated PV/PCM system and concluded than a lower temperature of a PV/PCM system leads to a rise in the value of the system's efficiency (Cellura et al., 2008).

Japs et al. (2013) proposed the modification of a single crystalline silicon PV module equipped with a conventional, commercially available PCM and another one with a new PCM compound featuring an increased thermal conductivity but lower heat storage capacity. Based on measurements of temperature development and daily electrical energy yield it was concluded that the higher heat storage capacity of conventional PCM leads to higher daily electrical energy yields and that higher thermal conductivity of the PCM leads to lower operating temperatures of the PV module (Japs et al., 2013).

Because for each 10 K increase in cell temperature above 298 K the power output decreases by about 0.4–0.6% and this will obviously depend on module design, it is therefore important to ensure excessive temperature is avoided as far as possible, for example by modification with phase change materials. The authors performed a number of experiments in different PV-PCM systems and analyzed the obtained results.

2. Characteristics of phase change materials

PCMs can be divided into three main groups: organic compounds (e.g., waxes, paraffins, fatty acids, alcohols), inorganic compounds (hydrated salts), and eutectic mixtures. These compounds have different phase change temperature ranges that determine their usability in specified applications (Huang et al., 2006).

Depending on the application, the PCMs should be selected based on their melting temperature, should have a large latent heat, should melt congruently with minimum subcooling, and

should be chemically stable, inexpensive, nontoxic, and non-corrosive.

The result of a differential scanning calorimetry (DSC) experiment is a curve of heat flux versus temperature level or time which can be used to calculate the enthalpy of transitions ΔH by integrating the peak corresponding to a given transition (ISO 6946:2007, 2007):

$$\Delta H(T) = \int_{T_0}^{T} C_p(T)dT \tag{1}$$

where ΔH [kJ] is the enthalpy of transition, $C_p(T)$ $\left[\frac{kJ}{K}\right]$ is the heat capacity at constant pressure, and T [K] is the temperature level.

In practice, Eq. (1) is simplified to:

$$\Delta H = k \cdot A \tag{2}$$

where k is the so-called calorimetric constant, which can be determined by analyzing a well-characterized sample with known enthalpies of transition, and A is the surface area under the curve, which can be determined, for example, by graphic integration.

Most organic PCMs are non-corrosive and chemically stable, exhibit little or no subcooling, are compatible with most building materials, and have a high latent heat per unit weight and low vapour pressure. Most of the PCMs undergo large changes in volume (approx. 10%) during melting. This may cause high stresses on the heat exchanger walls. Inorganic compounds have a high latent heat per unit volume and high thermal conductivity and are non-flammable and inexpensive in comparison to organic compounds. However, they are corrosive to most metals and suffer from decomposition and subcooling, which can affect their phase-change properties (Farid et al., 2004). Insufficient long-term stability of the storage materials and containers is a problem that has led to insufficient use of latent heat stores. This poor stability is due to two factors: poor stability of the materials' properties due to thermal cycling or corrosion between the PCM and the container (Zalba et al., 2003).

A relevant aspect is the useful life of these systems and the number of cycles they can withstand without any degradation of their properties. Hadjieva et al. (1992) verified the lack of effect of the cycles on the properties of paraffin and paraffin mixtures. Also, Gibbs and Hasnain (1995) confirmed that neither contact with metals nor the cycles degrade the thermal behaviour of paraffin and that it therefore has excellent thermal stability.

PCMs belonging to the macromolecular hydrocarbons (paraffins and waxes) may find applications in the stabilization of the temperature of PV modules, food, and building construction. These compounds have many advantages when used as PCMs; for example they have high thermal capacity and are nontoxic/safe, chemically neutral, reliable, non-corrosive, and inexpensive. However, organic PCMs also have some drawbacks such as low thermal conductivity of $\lambda \approx 0.2$ W/(m·K), a wide range of melting temperatures, low volumetric latent heat storage capacity, flammability, and the fact that pure paraffin waxes are very expensive (technical grade paraffins can be used).

3. Influence of temperature of photovoltaic cells on the electrical parameters of the module

On switching on the incident radiation an increase of the cell temperature is observed. The temperature of the PV cell increases with time, starting from the ambient temperature T_{amb} and rising to a higher value depending on the irradiance. The black or dark blue surface of a single-crystalline silicon solar cell is quite a good absorption layer, and its surface temperature can achieve a relatively high temperature (as much as 80 °C).

Solar cells and solar panels work best at certain temperatures according to their material properties. Many techniques have been tested to improve the overall efficiency of PV panels.

The most common are the use of anti-reflection coatings, radiation concentrators, and ventilation. Some researchers have used cooling water as a heat transfer material; however, such a solution proves to be quite expensive in the long term and liable to breaking due to leaks in such installations (Radziemska, 2003). PCMs, which are capable of stabilizing the temperature of PV cells of a PV/PCM system in the range of 25–30 °C, are promising materials to improve the efficiency of PV cells.

Solar radiation entering a solar cell changes its temperature due to the heat produced by: the absence of active absorption of photons, which do not generate pairs (electron–hole pairs), the recombination of electron–hole pairs outside the p-n junction region, photocurrent (Joule heat generated in the series resistance of the p-n junction and parasitic currents).

To compare the performance of different solar power modules, the following uniform operating data have been defined as the Standard Test Conditions (STCs): a cell temperature of 25 °C, solar irradiance of 1000 W/m², and air mass AM = 1.5.

STCs occur very rarely. The temperature of the module (cells) can rise much higher than the STC temperature, causing a drop of the power and efficiency of the crystalline silicon PV module with a coefficient of −0.4 to −0.65%/K above the STC temperature. At normal and lower temperatures of around 298 K, silicon is a good material, but at high temperatures such as 200 °C, its efficiency drops to 5%.

The temperature dependence of the solar-cell open-circuit voltage (V_{oc}) is given by Carlson (1989):

$$V_{oc}(T) = V_{oc}(T_0) - \left[\frac{E_{g0}}{e} - V_{oc}(T_0)\right]\left[\frac{T}{T_0} - 1\right] - \frac{3kT}{e}\ln\frac{T}{T_0} \qquad (3)$$

During the work of a solar cell, if the temperature rises by, say, 40 K in the case of T_0 = 300 K and T = 340 K, $\ln\frac{T}{T_0} \cong 0.125$ and $\frac{3kT}{e}\ln\frac{T}{T_0} \cong 10$ mV can be neglected. Thus, from Eq. (4) we get an approximately linear function:

$$V_{oc}(T) = V_{oc}(300\ \text{K}) - const(T - 300\ \text{K}) \qquad (4)$$

The change of V_{oc} with temperature as calculated from Eq. (4) is:

$$\frac{dV_{oc}}{dT} = -\frac{\frac{E_{g0}}{e} - V_{oc}(T_0)}{T_0} - \frac{3k}{e} \qquad (5)$$

In the case of T_0 = 300 K, E_{g0} = 1.21 eV, and V_{oc} (T_0) = 0.55 V, which is typical for a silicon solar cell, from (6) we get a decrease in V_{oc} with increasing temperature of $\frac{dV_{oc}}{dT} = -2.45\ \frac{mV}{K}$ or about $-0.4\frac{\%}{K}$, measured relative to V_{oc} at 25 °C (Bhargava et al., 1991). This value is also in agreement with the findings of Green (1992).

The electrical efficiency η_{el} is given as a function of temperature:

$$\eta_{el} = \eta_0[1 + \beta(T_{cell} - 298\ \text{K})] \qquad (6)$$

The silicon efficiency temperature coefficient $\beta = -4.5 \cdot 10^{-3}\ \text{K}^{-1}$ (Zondag et al., 2002), $\beta = -6.6 \cdot 10^{-3}\ \text{K}^{-1}$ (Radziemska, 2003), or $\beta = -6.4 \cdot 10^{-3}\ \text{K}^{-1}$ (Tripanagnostopoulos et al., 2002).

The maximum output power P_{MPP} (MPP is the maximum power point) is the point on the current–voltage (I–V) curve of a solar module that defines the largest possible rectangle area under the curve (Fig. 1). This point can be found by simultaneously drawing the I–V curve and the power–voltage (P–V) curve of the module at constant temperature and irradiance on the same graph (Fig. 2.). Another way is to draw the hyperbola of constant power or, by rough approximation, the slope of the I–V curve equal to negative one (Stamenic et al., 2000). If the temperature of the module increases from 25 to 70 °C, the voltage at the MPP (V_{MPP}) decreases significantly.

A linear decrease of the maximum output power P_{MPP} with increasing temperature has been observed and the temperature coefficient was derived in Radziemska and Klugmann (2006): $\alpha P_{MPP} = -0.65\%/\text{K}$, in conformity with the experimental investigations on several silicon solar cells and the results of our paper (Radziemska and Klugmann, 2002).

4. Experimental procedure

The experimental apparatus consisted of the PV/PCM experimental test system, a solar simulator – light source, and a data acquisition system.

Using the results of our own measurements or those published by other researchers and knowing the energy value E [W h/m² day] that should be drained from the module surface, on the basis of the value of PV efficiency, we can calculate the sufficient thickness of the PCM:

$$dQ = \varrho_{PCM} \cdot A\,dx\left[c_p(t_m - t_1) + h + c_p(t_2 - t_m)\right] \qquad (7)$$

Then: $x = \dfrac{E_{day} \cdot (1 - \eta) \cdot A}{\varrho_{PCM} \cdot A\left[c_p(t_m - t_1) + h + c_p(t_2 - t_m)\right]}$ $\qquad (8)$
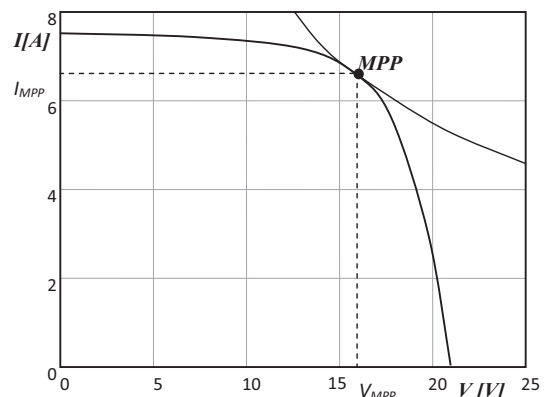

Fig. 1. Current–voltage output curve of the PV module under STCs of irradiance = 1000 W/m² and cell temperature = 25 °C.
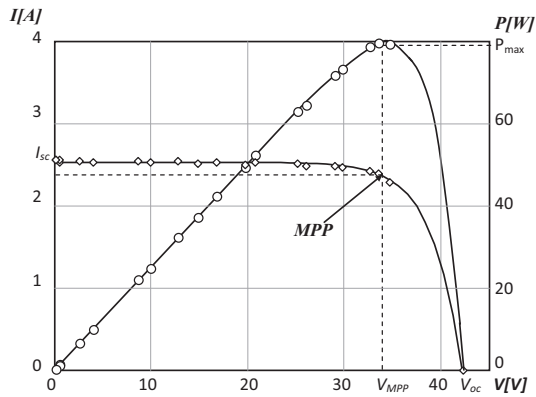
Fig. 2. Current–voltage characteristic, *I–V*, and output power versus voltage, *P–V*, of the PV module measured under STCs.

To reduce the temperature of the PV module, a layer of proper PCM with a thickness of 0.02, 0.03, or 0.05 [m] was applied on the rear surface of the PV module, with the option of water cooling of the PCM layer. The heat transferred through the PCM layer should drain the redundant heat from the module (see Fig. 3).

In the experiment, a PV module produced by Celine Company (http://www.celine-PV-power.com) was used. Its parameters under STCs of $G = 1000$ W/m^2 and $t_c = 25$ °C are presented in Table 1.

The module was modified with three selected PCMs (PCM1, PCM2, and PCM3), whose thermophysical properties are shown in Table 2.

Differential scanning thermographs of the selected PCMs are presented in Fig. 4.

Use of the artificial light source HL 313.01 provides illumination for indoor operation of solar training units. This light source allows experimentation under stable and reproducible irradiation conditions. The intensity can be altered by changing the distance to the respective light absorber under test. Thanks to this, the tested PV module, which had an area smaller than the illuminated area, was illuminated evenly during the experiment. Since there is no scale effect for the efficiency of PV modules, the module uses a relatively small size for the sake of convenience.

The temperature of the modules was measured with the use of a BP21 laser pyrometer and a Fluke type TiR 3 thermovision camera. These devices allowed for remote and non-contact measurement of the temperature distribution of the PV module. The measurements were performed at 1–2 m from the test object. Thermograms were obtained using the program SmartView.
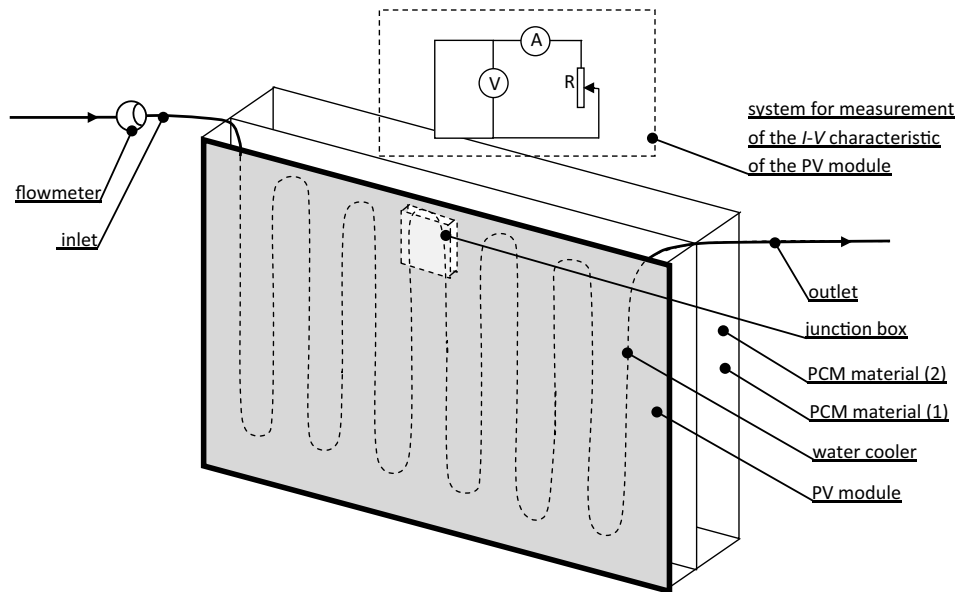

Fig. 3. Experimental stand for PV/PCM examination.

Table 1
Photovoltaic module parameters.

Module type	CL010-12
Maximum power (P_{MPP}) [W]	10.0
Nominal voltage [V]	12.0
Maximum power point current (I_{MPP}) [A]	0.57
Maximum power point voltage (V_{MPP}) [V]	17.5
Short circuit current (I_{SC}) [A]	0.63
Open cell voltage (V_{OC}) [V]	22.0
Dimensions (width × height × depth)	$340 \times 280 \times 17$ mm

In order to determine the current–voltage characteristics of the module, the experiment was conducted in the laboratory using a halogen lamp with a power of 8 kW (G.U.N.T. Gerätebau GmbH) and a radiation intensity in the range of 950–1050 W/m². The intensity of the radiation was measured using an SP Lite-2 pyranometer (Kipp & Zonen).

The measurements were carried out by the comparative method, namely using an unmodified module and PV/PCM with a PCM layer on the rear side of the module with a water cooling option (system A-I, Table 3).

5. Experimental results

When the PV module is exposed to direct sunlight with a fixed value of intensity and is loaded at the MPP, its temperature increases for several hours until it reaches a maximum value. The results of the temperature of the loaded and illuminated module as a function of time are presented in Fig. 5.

The temperature of the module reaches a greater value when operating under artificial light than under natural sunlight, due to the different spectral characteristics of these light sources and the larger component of infrared radiation in the case of artificial light, even though the value of measured irradiation is the same.

At stabilized temperature and illumination, the electrical parameters of the PV cell were evaluated using an ammeter with a small internal resistance and a measuring error of 0.2% and a digital voltmeter with an input impedance of 10 MΩ with a small error of 0.06%.

Fig. 6 presents the current–voltage characteristics at a constant illumination of 1000 W/m² and module temperatures of 27, 33, 41, 45, 53, 57, 61, 64, 68, and 70 °C (ambient temperature: 23 °C).

The dominant influence of temperature results in an overall decrease of the maximum output power. The temperature mainly influences the open cell voltage as well as the fill factor, FF. The position of the MPP is dependent on the irradiance and temperature.

Most of the solar radiation absorbed by solar cells is not converted to electricity, and increasing their temperature reduces their electrical efficiency. Fig. 7 presents the efficiency of the module versus the temperature drawn on the basis of the data in Fig. 6 and previous research.

Table 2
Thermophysical properties of PCMs used for PV module modification. *Source:* https://www.merckmillipore.com.

|	PCM1: Paraffin 42–44 (Merck®)	PCM2: Rubitherm RT 22 (Rubitherm Technologies GmbH)	PCM3: Ceresin (LOTOS GROUP S.A.)
Colour	White	Colourless	Yellow
Form	Solid	Liquid/Crystals	Solid
Smell	Odourless	Odourless	Odourless
Solubility in water	Insoluble	N/A	Insoluble
Solubility in organic solvents	Soluble	N/A	Soluble
Melting temperature t_m [°C]	42–72	20–23	61–78
Freezing point t_c [°C]	42–44	22–23	61–78
Boiling temperature t_b [°C]	>300	N/A	>300
Ignition temperature t_z [°C]	>300	N/A	>250
pH	Neutral	N/A	Neutral
Density [g/cm³]	0.90 (20 °C)	0.76 (20 °C)	0.91 (20 °C)
			0.78 (100 °C)
Specific enthalpy h [kJ/kg]	130	200	160
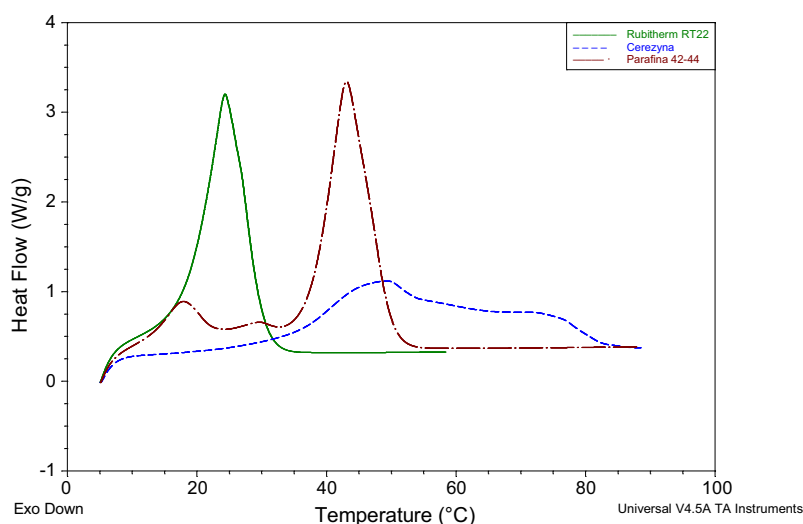
Fig. 4. Differential scanning thermographs of PCMs. Green line: RT22; blue line: ceresin, brown line: paraffin 42–44. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Tested PV/PCM systems.

Symbol	System description
A	Unmodified PV module, laboratory conditions
A1	Unmodified PV module, natural sun lighting conditions
B	PV with tin container without PCM, laboratory conditions
C	PV with tin container and PCM 1 (2 cm), laboratory conditions
D	PV with tin container and PCM 2 (2 cm), laboratory conditions
E	PV with tin container and PCM 3 (2 cm), laboratory conditions
G	PV with tin container, PCM 1 (2 cm), and water cooling (32 dm³/h), laboratory conditions
H	PV with tin container, PCM 1 (2 cm), and water cooling (80 dm³/h), laboratory conditions
I	PV with tin container, PCM 1 (3 cm), and water cooling (80 dm³/h), laboratory conditions
J	PV with tin container, PCM 1 (4 cm), and water cooling (80 dm³/h), laboratory conditions
K	PV with tin container and PCM 1 (2 cm) without water cooling, natural conditions
L	PV with tin container, PCM 1 (2 cm), and water cooling (80 dm³/h), natural conditions

One can see that at both low and elevated – relative to optimal – temperatures, a decrease in the efficiency of PV cells of all types except for the organic cells and cells of amorphous silicon is observed. For crystalline silicon cells, this optimal temperature is about 298 K.

In practice, the modules operate above the optimum temperature due to absorption of photons, which do not generate pairs, recombination of charge carriers, and Joule's heat of the photocurrent.

For the temperature range above 300 K, the electrical efficiency η_{el} is given as a linear function of temperature (6), where β is the silicon efficiency temperature coefficient, which is normally given by the PV manufacturer.

The aim of the research was to improve the electrical parameters of a loaded module. The optimum operating temperature of the module was stabilized by placing an appropriate amount of PCM (PCM1, PCM2, or PCM3) on the rear surface of the module (with and without water cooling). The aim of the modification was to reduce the operating temperature of the modules and to improve the efficiency of energy conversion.

The material finally selected as the best one to modify the PV module was paraffin. Rubitherm RT22 already becomes liquid at ambient temperature (in summer conditions), and ceresin in turn has temperature of phase transition that is too high and it remains in the solid phase.

The effect of lowering the temperature of the modified PV module for different examined systems under constant irradiation of 1000 W/m² is shown in Fig. 8.

On the basis of this analysis of results, the recommended system is H, a relatively thin layer of paraffin with water cooling.

The same was confirmed for natural sunlight conditions (systems K and L). Measurements were conducted from 9 am to 2 pm at a solar radiation intensity of 1000 W/m² (±10%). Due to variability in comparison to those obtained using the artificial light source, measurements were made with a higher frequency than in the laboratory. The study was conducted at ambient temperatures ranging from about 27 °C at 9 am to about 30 °C from noon until 2 pm. During the experiment, virtually windless conditions prevailed, with rare, gentle, warm gusts. The measurements were performed for the systems K and L to give the same results as for systems C and H.

Despite of this, that the best results were obtained using system with paraffin and cooling water, it is more convenient and cheaper to apply modifications of the module with paraffin without cooling.

Comparing these results with the results of earlier studies on the use of water cooling to increase the efficiency of PV modules (Klugmann-Radziemska and Lewandowski; Radziemska, 2003, 2007; Klugmann and Radziemska, 2000), it can be stated that the application of the PCMs, especially paraffin, may be an alternative to water cooling. In the previous experiments, several advantages associated with the water cooling of the PV module have been observed, namely increases in the output power, open circuit voltage, and PV conversion efficiency. The energetic conversion efficiency of the PVT integrated system is higher than the efficiency of an analogous separate heat collector.

However, water cooling also has some drawbacks associated with the transport of liquid to the PV/T system, often over a considerable distance, which requires the supply pumps to provide circulation.

The use of paraffin in the proposed PV/PCM system makes it possible to avoid the problem of corrosion, which occurs not only in the case of water cooling but also in the case of PCMs using materials in the form of hydrated salts.

Since researchers often quote the kWp output of a PV panel tested in the literature, the power generation analysis for PV system with nominal power of 1kWp (unmodified and modified: PV module with a steel tank filled with PCM1 (42–44 paraffin) with a thickness of 2 cm without water cooling) was carried out on the base of Photovoltaic Geographical Information System (Šúri et al., 2007; Huld et al., 2012). The calculations have been made with
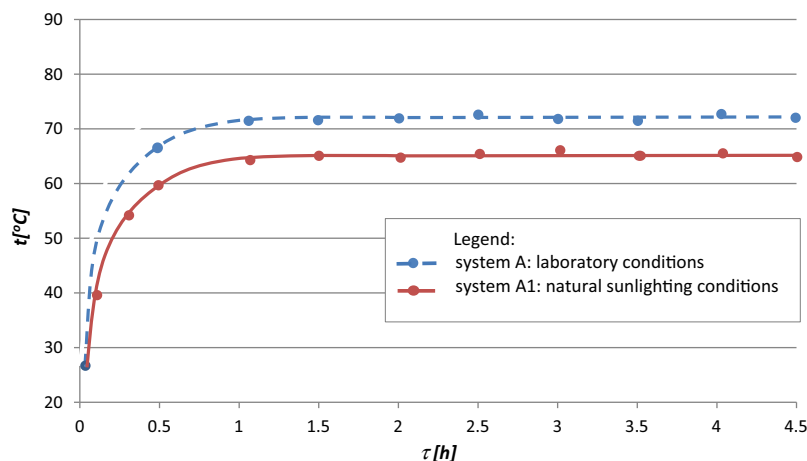
Fig. 5. Temperature rise of unmodified PV solar module under constant irradiation as a function of operation time.
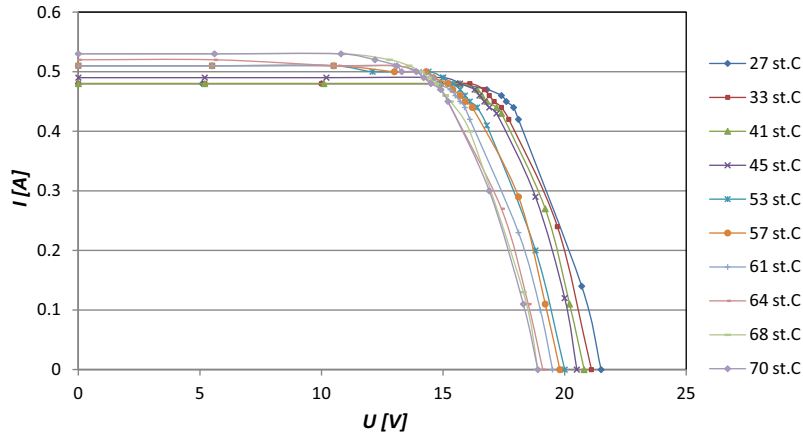
Fig. 6. Current–voltage characteristics of tested PV module at different temperatures of the module and constant irradiation of 1000 W/m².
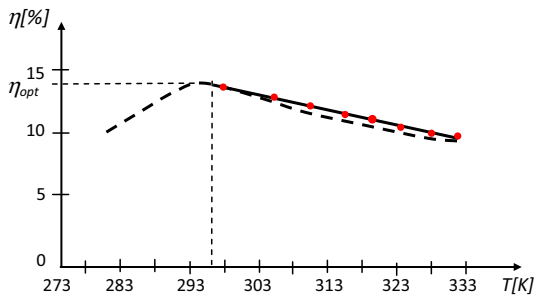

Fig. 7. Temperature dependence of the crystalline PV module's efficiency (dotted line: Klugmann-Radziemska and Lewandowski; solid line with points: current research).

Poland and its weather conditions in mind. However, annual irradiation is similar in much of Northern Europe.

The output from a PV installation is the output of the PV array less the losses in the rest of the system. It was assumed that for crystalline silicon the combined system losses are equal to 23.4% (including estimated losses due to temperature and low irradiance: 6.4%, using local ambient temperature, estimated loss due to angular reflectance effects: 3.0% and other losses - cables, inverter: 14.0%).

For fixed photovoltaic system with optimal inclination of 35° and orientation of 0° (faced to South) electricity production from the 1 kWp unmodified PV system is 1010 kW h per year. For modified PV/PCM with temperature coefficient of PV module equal to 0.0065 K^{-1} (Radziemska, 2003; Tripanagnostopoulos et al., 2002) and estimated system loses of 18.8% the energy production will
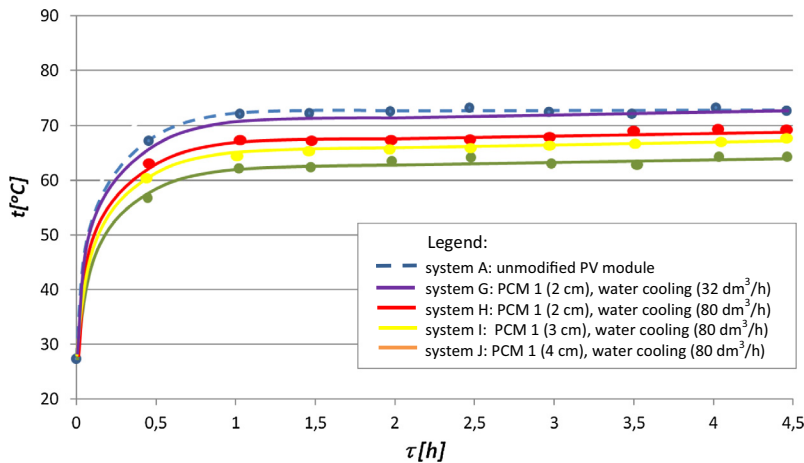

Fig. 8. Temperature rise of modified PV solar module under constant irradiation as a function of operation time.

Table 4
Power generation and economic analysis for PV and PV/PCM system.

Parameters	PV system (unmodified)	PV/PCM system (PV module with a steel tank filled with PCM1 (42–44 paraffin) with a thickness of 2 cm without water cooling)
Nominal power	1kWp	1kWp
Combined system losses	23.4%	18.8%
Electricity production per year	1010 kW h	1080 kW h
Energy surplus per 30-year period	0	2100 kW h
Economic surplus per 30-year period	0	250€

be 7% larger and will rise to 1080 kW h/year. For the assumed 30-year exploitation period of the installation this additional profit will be equal more than the 2-year production value (additional 2100 kW h/year).

The economic analysis is also promising: with current market trends and cost reduction opportunities, utility scale system costs was expected to reach $2.20/watt by the end of 2016 (Photovoltaic Systems, 2010), what means that the cost of 1kWp installation is currently 2000 €.

The wholesale price of paraffin is $ 1000 per tonne, which means that the modification of modules with a nominal power of 1kWp costs around 170 €.

A surplus of produced during 30-year period 2100 kW h gives a profit of 420 €, therefore balance gives a profit of 250 € (more than 10% of the overall cost of 1kWp installation) (Table 4).

6. Conclusions

A large part of the PV conversion losses are related to the temperature increase of the solar cells. Maintaining the temperature of the module at an optimum level was the aim of this study.

Experimental research on a silicon PV module in a PV/PCM system in which the optimum operating temperature of the cell was stabilized through the use of a suitably selected PCM has been conducted. Measurements of electrical parameters of the loaded modules under constant intensity of radiation and with various configurations of the system were performed.

An appropriately selected PCM should be used for the PV module modification: the basic criterion is a suitable melting point, which must be higher than 30 °C, so that the material remains in the solid state under ambient temperature in the summer season. At the same time, the material should possess the highest possible enthalpy change h.

The results show that, for constant solar irradiance, the unmodified solar PV module heats up to a higher temperature than one in a PV/PCM system. The modification also made it possible to obtain higher values of maximum power (P_{MPP}) and efficiency (η) than the unmodified module. The best results were obtained for the PV/PCM configuration of a PV module with a steel tank filled with PCM1 (42–44 paraffin) with a thickness of 2 cm and water cooling, but the PV/PCM with water cooling is not worthwhile for future application due to technical difficulties of such solution, the need for a pump system, possible corrosion and increased system weight. In practice, it is more convenient and cheaper to apply modifications to the module with PCM without cooling. This made it possible to lower the temperature of the module by 7 K.

Maintaining a reduced temperature of the module during intense solar radiation for more than five hours will increase the efficiency of the module in this most efficient period of the day, while the losses associated with maintaining the temperature of the module near the melting point of the PCM in the afternoon, when the ambient temperature goes down, are smaller due to the much lower yields of energy because the solar radiation is of low intensity.

The utilization of PCM constitutes a simple and low-cost method of removing heat from a PV module and keeping the electrical efficiency at an acceptable level.

Acknowledgements

References

Bhargava, A.K., Garg, H.P., Agarwal, R.K., 1991. Study of a hybrid solar system - solar air heater combined with solar cells. Energy Convers. Manage. 31, 471–479.

Carlson, D., 1989. Low-cost power from thin-film PV. In: Electricity, Lund University Press, Lund.

Cellura, M., Ciulla, G., Lo Brano, V., Marvuglia, A., Orioli, A, 2008. A photovoltaic panel coupled with a phase changing material heat storage system in hot climates. In: PLEA 2008–25th Conference on Passive and Low Energy Architecture, Dublin, October 2008.

Farid, M.M., Khudhair, A.M., Khateeb, S.A., Al-Hallaj, S., 2004. A review on phase change energy storage: materials and applications. Energy Convers. Manage. 45, 1597–1615.

Gibbs, B.M., Hasnain, S.M., 1995. DSC study of technical grade phase change heat storage materials for solar heating applications. In: Proceedings of the 1995 ASME/JSME/JSEJ International Solar Energy Conference, Part 2.

Gkouskos, Z., Tsoutsos, T., Kakouriotis, A., 2012. Integrating phase change materials to photovoltaics in a mediterranean region. In: 27th European Photovoltaic Solar Energy Conference and Exhibition, Frankfurt, pp. 305–310.

Green, M.A., 1992. Solar Cells. University of New South Wales, Kensington.

Hadjieva, M., Kanev, S., Argirov, J., 1992. Thermophysical properties of some paraffins applicable to thermal energy storage. Sol. Energy Mater. Sol. Cells 27, 181–187. http://dx.doi.org/10.1016/0927-0248(92)90119-A.

Hasan, A., McCormack, S.J., Huang, M.J., Norton, B., 2010. Evaluation of phase change materials for thermal regulation enhancement of building integrated photovoltaics. Sol. Energy 84, 1601–1612. http://dx.doi.org/10.1016/j.solener.2010.06.010.

Huang, M.J., Eames, P.C., Norton, B., 2004. Thermal regulation of building-integrated photovoltaics using phase change materials. Int. J. Heat Mass Transf. 47, 2715–2733. http://dx.doi.org/10.1016/j.ijheatmasstransfer.2003.11.015.

Huang, M.J., Eames, P.C., Norton, B., 2006. Phase change materials for limiting temperature rise in building integrated photovoltaics. Sol. Energy 80, 1121–1130. http://dx.doi.org/10.1016/j.solener.2005.10.006.

Huld, T., Müller, R., Gambardella, A., 2012. A new solar radiation database for estimating PV performance in Europe and Africa. Sol. Energy 86, 1803–1815.

EN ISO 6946:2007. Building components and building elements. Thermal resistance and thermal transmittance. Calculation method.

Japs, E., Sonnenrein, G., Steube, J., Vrabec, J., Kenig, E., Krauter, S., 2013. Technical investigation of a photovoltaic module with integrated improved phase change material. In: 28th European Photovoltaic Solar Energy Conference and Exhibition, Paris 2013, pp. 500–502.

Klugmann, E., Radziemska, E., 2000. Lewandowski, Influence of temperature on conversion efficiency of a solar module working in photovoltaic PV/T integrated system. In: 16th European Photovoltaic Solar Energy Conference and Exhibition, United Kingdom, Glasgow, 1–5 May 2000, pp. 2406–2409.

Klugmann-Radziemska, E., Lewandowski, W. Polish Patent Office, Patent No. 203881: Integrated photovoltaic module with heat solar collector.

Leenders, F., Schaap, A.B., Vander Ree, B.G.C., Van der Holden, W.G.J., 2000. Technology review on PV/thermal concepts. In: 16th European Photovoltaic Energy Conference, Glasgow, pp. 1976–1980.

Malvi, C.S., Dixon-Hardy, D.W., Crook, R., 2011. Energy balance model of combined photovoltaic solar-thermal system incorporating phase change material. Sol. Energy 85, 1440–1446. http://dx.doi.org/10.1016/j.solener.2011.03.027.

$1/W Photovoltaic Systems, 2010. White paper to explore a grand challenge for electricity from solar. U.S. Department of Energy.

Radziemska, E., 2003. The effect of temperature on the power drop in crystalline silicon solar cells. Renewable Energy 28, 1–12. http://dx.doi.org/10.1016/S0960-1481(02)00015-0.

Radziemska, E., 2003. The effect of temperature on the power drop in crystalline silicon solar cells. Renewable Energy 28, 1–12.

Radziemska, E., 2007. PVT – hybrid photovoltaic - thermal solar systems. In: XXXI International Conference of IMAPS Poland Chapter, Krasiczyn, 23–26 September 2007, pp. 433–436.

Radziemska, E., Klugmann, E., 2002. Thermally affected parameters of the current-voltage characteristics of silicon photocell. Energy Convers. Manage. 43 (14), 1889–1900.

Radziemska, E., Klugmann, E., 2006. Photovoltaic maximum power point varying with illumination and temperature. J. Sol. Energy Eng., Trans. ASME 128, 34–39.

Sopian, K. et al., 1996. Performance analysis of photovoltaic thermal air heaters. Energy Convers. Manage. 37, 1657–1670.

Stamenic, L. et al., 2000. Novel microprocessor controlled real time MPPT for PV charging applications. In: Proc. of 16th European PV Solar Energy Conference and Exhibition, Glasgow, UK, p. 2434.

Šúri, M., Huld, T.A., Dunlop, E.D., Ossenbrink, H.A., 2007. Potential of solar electricity generation in the European Union member states and candidate countries. Sol. Energy 81, 1295–1305.

Tripanagnostopoulos, Y., Nousia, T.H., Souliotis, M., Yianoulis, P., 2002. Hybrid photovoltaic /thermal solar systems. Sol. Energy 72 (3), 217.

Zalba, B., Marín, J.M., Cabeza, L.F., Mehling, H., 2003. Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. Appl. Therm. Eng. 23, 251–283.

Zondag, H.A. et al., 2002. The thermal and electrical yield of a PV-thermal collector. Sol. Energy 72 (2), 113.