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Increasing the efficiency of PV panel with the use of PCM

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A R T I C L E I N F O

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A B S T R A C T

The article presents how to increase electrical efficiency and power output of photovoltaic (PV) panel with the use of a phase change material (PCM). The focus of the work is in experimental setup and simulation heat extraction from the PV panel with the use of TRNSYS software. A modification of PV panel Canadian Solar CS6P-M was made with a phase change material RT28HC. The actual data of cell temperature of a PV panel with and without PCM were given and compared. A simulation of both PV panels in TRNSYS software was performed, followed by the comparison of results with the simulation and experimental actual data. The experimental results show that the maximum temperature difference on the surface of PV panel without PCM was 35.6 °C higher than on a panel with PCM in a period of one day. Referring to experimental results the calculation of the maximum and average increase of electrical efficiency was made for PV-PCM panel with TRNSYS software. Final results of simulation shows that the electricity production of PV-PCM panel for a city of Ljubljana was higher for 7.3% in a period of one year.

1. Introduction

Photovoltaic panels absorb a large part of the solar energy nevertheless they converted only a small part of this solar energy into electricity. The process of direct conversion is carried out in a variety of solar cells. The efficiency of conversion of solar energy into electric energy is strongly dependent on the type of the solar cell and the operating conditions. PV cells convert a certain wavelength of the incoming irradiation that contributes to the direct conversion of light into electricity, while the rest is dissipated as heat. Only 15–20% of incident solar energy is converted into electricity. The remaining part of the solar energy is converted into heat, which causes heating of the solar cells in PV panels. The surface of the PV panel can be heated up to 40 °C above ambient temperature [1]. Increasing the temperature of the solar cells causes drop of the electrical efficiency of a photovoltaic panel. Conversation efficiency of PV panel decreased by 0.4% to 0.65% for every increased degree of PV cells temperature [2]. E. Radziemska concluded in her work that the electrical efficiency of PV panels fall by 0.08% for 1 °C increase in temperature of PV panel above 25 °C and reducing the power output of PV panel by 0.65% [3].

To increase efficiency, it is better if the PV panel is cooled. PV panels can be cooled in several ways: active or passive. Active cooling of a photovoltaic panel is usually performed by liquid or gas. Active cooling systems comprise of heat extraction utilizing devices such as fans to force air or pump water to the panels to extract away the heat. Wide varieties of passive cooling options are available, simplest forms involve application of solids of high thermal conductivity metals, such as aluminium and copper, or an panel of fins or other extruded surfaces to enhance heat transfer to the ambient. More complex systems involve the use of PCM. However, in such cooling systems heat dissipation is limited by the contact point between the heat-sink and the ambient, where the convective heat transfer coefficient and the radiative heat transfer are limiting factors [4]. Cooling the PV panels with PCM is preferable because does not need any additional energy for cooling [5]. Ideal PCM for cooling PV panel must have large latent heat of fusion, high thermal conductivity, be chemically stable, non-corrosive, non-toxic, melt temperature lying in the operating temperature of the PV panel and minimum sub cooling [6]. One of the most challenging tasks is to ensure high thermal conductivity of PCM from previous mentioned properties. One of options is to insert fins for heat transfer extraction [7]. With the removal of excess heat out of the PV panel we achieved lower temperature of the PV cells and higher production of electricity. A PV panels which are cooled and uses the excess heat for further application are called PV-T.

Studies shows that PV-T technology is very promising and has a very large potential in the coming years, because the energy generated from renewable resources increases every year and this technology can be used in many different systems [8]. Recent

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Nomenclature

η	the overall efficiency of the photovoltaic array
η_{ref}	the overall efficiency of the photovoltaic array under reference conditions
$\eta_{T,coef}$	a coefficient that describes the change in PV efficiency as a function of cell temperature
$\eta_{I,coef}$	a coefficient that describes the change in PV efficiency as a function of incident solar radiation
T_{PV}	the PV cell temperature (K)
T_{ref}	cell temperature under which the reference PV efficiency was measured (K)
T_C	the PV cover temperature (K)
T_B	the PV back surface temperature (K)
T_{PCM}	the phase change material temperature (K)
$T_{amb,top}$	the temperature to which the PV convectively loses energy off its top surface (K)
$T_{amb,back}$	the temperature to which the PV convectively loses energy off its back surface (K)
$T_{rad,top}$	the temperature to which the PV radiatively loses energy off its top surface (K)
$T_{rad,back}$	the temperature to which the PV radiatively loses energy off its back surface (K)
$T_{solidification}$	the temperature of solidification of PCM
$T_{liquefacation}$	the temperature of liquefaction of PCM
I_T	the total amount of solar radiation incident on the PV collector surface (kJ/h m^2)
$I_{T,ref}$	the total amount of solar radiation incident on the PV collector surface at the conditions under which the reference PV efficiency was measured (kJ/h m^2)
$\dot{P}_{PV}$	energy flux density generated by the PV (kJ/h m^2)
$(\tau\alpha)_n$	the transmittance/absorptance product of the PV cover for solar radiation at a normal angle of incidence
IAM	the combined incidence angle modifier for the PV cover material
A	the PV surface area (m^2)
R_1, R_2, R_3	the thermal resistance of the cover material, PV cell backing, and back insulation materials (h m^2 K/kJ)
$h_{conv,top}$	the convective heat transfer coefficient for the top surface of the PV (kJ/h m^2 K)
$h_{conv,back}$	the convective heat transfer coefficient for the back surface of the PV (kJ/h m^2 K)
$h_{rad,top}$	the radiative heat transfer coefficient for the top surface of the PV (kJ/h m^2 K)
$h_{rad,back}$	the radiative heat transfer coefficient for the back surface of the PV (kJ/h m^2 K)
h_{fg}	latent heat of solidification or latent heat of liquefaction of the PCM material (kJ/kg)
m	mass of the PCM layer (kg)
X	PCM material quality (0: completely liquid, 1: completely solid)
S	energy balance factor (kJ/h m^2)
Q	amount of heat (kJ)

research in the field of passive cooling of PV panels with PCM has shown that the PCM may store a large amount of heat and when cooling the PV panel with PCM it keeps almost constant temperature. Various PV-PCM concept designs have been reported in literature. In one of the research at Dublin institute of Technology they were used and tested four different types of PV panels, which are cooled by using the PCM. As it turned out the PV panel with the PCM had higher efficiency than normal PV panel, due to the lower temperature of the cells and consequently the degradation of the materials are longer [9]. The most common system studied considers incorporation of PCMs in Building Integrated Photovoltaic (BIPV) [9–11]. Stand-alone PV collectors with PCM thermal storage have also been reported in few literature [10,12]. The effect of crystalline segregation and convection in melted PCM was also investigated by Huang and results showed that with certain fin interval (12–24 mm) the thermal stratification could be reduced and convection had improved effect on heat transfer rate leading to more uniform temperature distribution in the PV-PCM system [13]. Studies about electricity power generation and efficiency show that the amount of electric power generation of PV-PCM was increased by 1.0–1.5% compared to that of the conventional PV module and efficiency of the PV-PCM module was increased by about 3.1% [14] and in Europe, the energy output enhancement varies between 2% and nearly 5% for some regions is possible for 6% [15].

The purpose of this study is to present how to increase the electrical efficiency of conventional PV panel and maintain lower temperature during the day with the use of PCM. The idea of including a PCM layer in a PV panel is that PVs are more efficient at lower cell temperatures. Where the cells in a standard PV panel heat up, the PCM layer in a PV-PCM absorbs incident solar energy that is not being converted to electrical energy by the PV cells and melts, keeping the PV cells cooler and more efficient. The aim of study is to demonstrate the effect of latent cooling on the conventional PV panel by using phase change material RT28HC. Depending on the work E. Radziemska the calculation of increased production of electricity was made due to cooling effect of PV panel with the PCM compared to regular PV panel. In conclusion, the simulation results of both PV panels were made for a period of one year for the city of Ljubljana.

2. Methodology

2.1. Experimental setup

For experimental setup and measurements the modification of conventional PV panel with phase change material was made [16], represented in Fig. 1 on the left. Chosen conventional PV panel was CS6P-M from company Canadian solar and PV cell was

Fig. 1. Conventional PV panel before (left) modification and after (right) modification.

manufactured using a monocrystalline silicon solar cell. The PCM was attached on back side of the PV module and enclosed with acrylic glass.

The final PV-PCM after modification is represented in Fig. 1 on the right.

Fig. 2 shows schematic diagram, construction of manufactured PV-PCM panel and thickness of each layer. PV-PCM are in fact encapsulated and consist of 7 layers of which are tempered Glass, ethylene-vinyl acetate (EVA), Si-solar cells, EVA, tedlar foil, PCM and transparent acrylic glass. The detailed electric properties of the PV cell are shown in Table 1.

The thermophysical properties of PCM, which is used in experimental study, are listed in Table 2.

The PCM in the modificated PV-PCM panel is paraffinic organic type RT28HC. RT28HC is a pure PCM and this heat storage material utilizing the processes of phase change between solid and liquid (melting and congealing) to store and release large quantities of thermal energy at nearly constant temperature. The phase change materials provide a very effective means for storing heat and cold, even when limited volumes and low differences in operating temperature are applicable. Experimental setup consists of PV-PCM panel, PV panel without PCM, three thermocouples for temperature measurement with Almemo 2690-8 and PC for data storage. During the experiment, the temperatures of the each of the panel were measured and the surrounding air temperature.

The temperature was measured at two points on the front of the panels and surrounding temperature behind the panels, as illustrated in Fig. 3. The data obtained from the measurement were stored in PC for further analysis. The measurement items and devices are listed in Table 3. The experiment was conducted on the terrace of the Faculty of Mechanical Engineering in Ljubljana.

2.2. Simulation model

For simulation TRNSYS simulation software with type 601 was used [19]. Type 601 is a glazed photovoltaic panel that includes a layer of phase change material. The model bases its electrical performance calculation on a user provided overall panel efficiency. Efficiency may be constant, variable, provided as a function of cell temperature and incident radiation in an external file or provided for reference conditions along with coefficients that describe the effect of cell temperature and incident radiation changes. Type 601 includes four modes of calculating PV performance with an embedded PCM layer depending on available data. The second mode of operation was used for simulation, in which the user provides efficiency information for reference conditions as well as coefficients that describe how the overall efficiency changes with cell temperature and incident solar radiation. A physical property of heat transfer in the PV-PCM panel is shown in Fig. 4 below.

The overall efficiency of the PV is calculated based on Eq. (1).

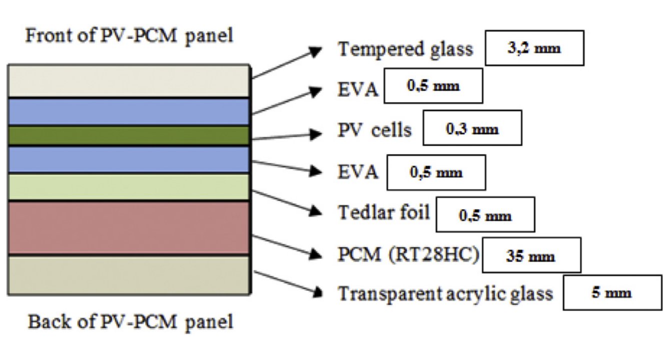

Fig. 2. Schematic diagram of PV-PCM panel after modification.

Table 1
Electrical properties of the PV model [17].

Property	Value
Maximum power (Pmax) (W)	250 W
Voltage at Pmax (V)	30.4 V
Current at Pmax (A)	8.22 A
Open-circuit voltage (Voc) (V)	37.5 V
Short-circuit current (Isc) (A)	8.74 A
Temperature coefficient of power (%/K)	−0.45
Temperature coefficient of Voc (%/K)	−0.35
Temperature coefficient of Isc (%/K)	−0.06
Cell type (−)	Monocrystalline
Module efficiency (%)	15.54
Dimensions (mm)	1638 (h) × 982 (w) × 40 (d)
Weight (kg)	20

Table 2
Thermal properties of the PCM [16].

Thermal property	Value
Melting peak (°C)	28
Latent heat of fusion (kJ/kg)[a]	245
Thermal conductivity (W/m K)	0.2
Density (solid) (kg/m^3)	880
Density (fluid) (kg/m^3)	770
Specific heat capacity (kJ/kg K)	2

[a] Temperature range 294–309 K.

$$\eta = \left(1 + \eta_{T,coef}\left(T_{PV} - T_{ref}\right)\right)\cdot\left(1 + \eta_{I,coef}\left(I_T - I_{T,ref}\right)\right)\eta_{ref} \quad (1)$$

Where, η is the overall efficiency of the photovoltaic system, $\eta_{T,coef}$ is a coefficient that describes the change in the PV efficiency as a function of the cell temperature, T_{PV} is the PV cell temperature, T_{ref} is the cell temperature at the conditions under which the reference PV efficiency was measured, $\eta_{I,coef}$ is a coefficient that describes the change in the PV efficiency as a function of the incident solar radiation, I_T is the total amount of solar radiation on the PV surface, $I_{T,ref}$ is the total amount of solar radiation on the PV surface at the conditions under which the reference PV efficiency was measured and η_{ref} is the overall efficiency of the photovoltaic panel under the reference condition.

$$\dot{P}_{PV} = (\tau\alpha)_n IAM I_T \eta A \quad (2)$$

The energy flux density produced by the PV-PCM module is calculated using Eq. (2), where is $\dot{P}_{PV}$ the electric power produced by the PV-PCM module, $(\tau\alpha)_n$ is the transmittance and absorptance product of the PV cover for solar radiation at a normal angle of incidence, *IAM* is the combined incidence angle modifier for the PV cover material, and *A* is the PV surface area. With Eqs. (1) and (2) the overall efficiency and the electric power produced of PV-PCM can be calculated, if the PV cell temperature is calculated through the energy balance between the layers in the PV-PCM panel. PV cell temperature is determined by the amount of incident solar radiation and heat transfer within the layers of the PV-PCM panel. In this study the PV-PCM panel studied with 4 layers, which is top transparent cover (tempered glass), PV cells (EVA foil, PV cell, EVA foil, tedlar foil), PCM and collector back (transparent acrylic glass).

$$\frac{T_{PV} - T_C}{R_1} = h_{conv,top}\left(T_C - T_{amb,top}\right) + h_{rad,top}\left(T_C - T_{rad,top}\right) \quad (3)$$

The energy balance on the top transparent cover is given by Eq. (3) for a PV-PCM panel that includes a transparent glazing that protects the PV cells from ambient conditions. Where is T_C the cover

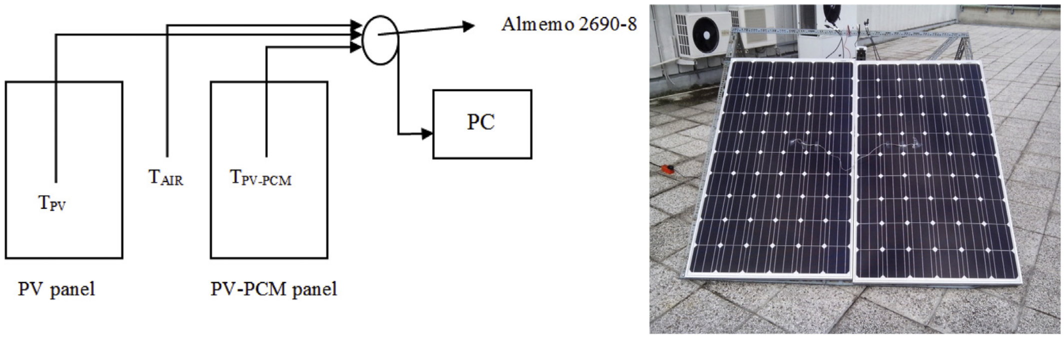

Fig. 3. Schematic diagram of experimental setup (left), front side of PV and PV-PCM panel with thermocouples for temperature measurement (right).

Table 3
Source of the measurement items.

Items	Device or reference	Accuracy
Temperature of PV-PCM	Thermocouple	0.1 K
Temperature of PV	Thermocouple	0.1 K
Air temperature	Weather station[a]	/
	Thermocouple	0.1 K
Solar irradiation	Weather station[a]	/
Data storage	Ahlborn Almemo 2690-8	/

[a] (Ljubljana-Bežigrad) (Slovenian Environment Agency (ARSO)) [18].

temperature, R_1 is the thermal resistance of the cover material,$h_{conv,top}$ is the convective heat transfer coefficient for the top surface of the PV-PCM, $T_{amb,top}$ is the temperature to which the PV-PCM convectively loses energy off its top surface, $h_{rad,top}$ is the radiative heat transfer coefficient for the top surface of the PV-PCM, and $T_{rad,top}$ is the temperature to which the PV-PCM radiatively loses energy off its top surface.

$$S = \frac{(T_{PV} - T_C)}{R_1} + \frac{(T_{PV} - T_{PCM})}{R_2} \tag{4}$$

The energy balance on the PV cells is given by Eq. (4), where is T_{PCM} the temperature of phase change material and R_2 is the thermal resistance of the PV cell backing and insulation materials.

$$mc_p \frac{dT_{PCM}}{dt} = \frac{(T_{PV} - T_{PCM})}{R_2} - \frac{(T_{PCM} - T_B)}{R_3} \tag{5}$$

$$\frac{(T_{PCM} - T_B)}{R_3} = h_{conv,back}(T_B - T_{amb,back}) + h_{rad,back}(T_B - T_{rad,back}) \tag{6}$$

Eqs. (5) and (6) represent the energy balance on PCM layer and on the back surface. In Eq. (5) is m the mass of PCM, c_p is the liquid or solid phase specific heat, R_3 is the thermal resistance of the PV-PCM back cover material and T_B is temperature of back surface of the PV-PCM panel. In Eq. (6) $h_{conv,back}$ is the convective heat transfer coefficient for the back surface of the PV-PCM, $h_{rad,back}$ is the radiative heat transfer coefficient for the back surface of the PV-PCM, $T_{amb,back}$ is the temperature to which the PV-PCM convectively loses energy off its back surface and $T_{rad,back}$ is the temperature to which the PV-PCM radiative loses energy off its back surface.

For the two phase region between the liquefaction and solidification temperature additional equations should be applied, because during the phase change the temperature of the PCM stays almost the same. The total energy required to fully melt of fully solidify the PCM material is represented in Eq. (7).

$$Q_{solidification} = Q_{liquefaction} = mh_{fg} \tag{7}$$

Here, is h_{fg} represent latent heat of solidification or liquefaction of

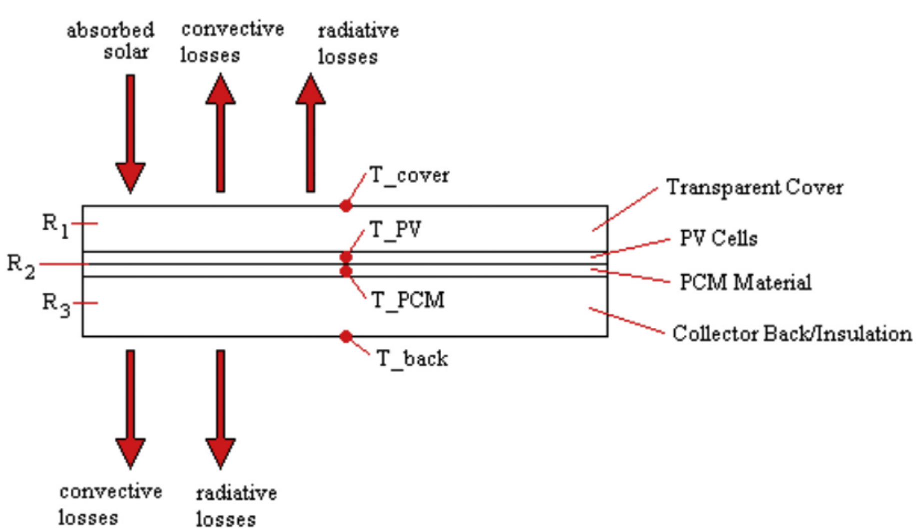

Fig. 4. PV-PCM panel configuration [19].

the PCM material, $Q_{solidification} = Q_{liquefaction}$ is the energy needed per unit mass to transform the PCM from 100% solid to 100% liquid and reverse, adding this much energy to the fully solidified PCM material moves it from a quality of 0 (completely solid) to a quality of 1 (completely liquid).

$$(X_{old} - X_{new})mh_{fg} = \dot{Q}_{added} \Rightarrow X_{new} = X_{old} - \frac{\dot{Q}_{added}}{mh_{fg}} \tag{8}$$

Therefore can write an expression for the change in PCM quality associated with the addition or removal of a known quantity of energy, which is in Eq. (8), where is X_{old},X_{new} quality of the PCM before and after each time step, $\dot{Q}_{added}$ is the added quantity of energy.

Based on the quality, the temperature of the two-phase PCM can be calculated as in Eq. (9).

$$T_{PCM} = \left(T_{liquefacation} - T_{solidification}\right)X_{new} + T_{solidification} \tag{9}$$

In Eq. (9) is $T_{liquefacation}$,$T_{solidification}$ the temperature of liquefaction and solidification of the PCM material. Using the above equations the temperature and heat balances of each layer of PV-PCM can be calculated. All of the equations were applied into a module type 601 and calculated using the energy simulation program TRNSYS.

Fig. 5 represents configuration for simulation in TRNSYS software with main type 601. Types 89a, 89a-2 and T9a includes input data, which are global solar radiation on a horizontal surface, direct solar radiation on a horizontal surface, diffuse solar radiation on a horizontal surface and the temperature of the ambient air for the city Ljubljana, Slovenia. The purpose of type T16a was to calculate the value of solar radiation on a tilted surface in our case 40°. Type 601d is our main module, represents PV panel with an embedded PCM layer for the simulation of PV-PCM panel, which contains the parameters from Tables 1 and 2 Type 25c is used for write results in an external file for further analysis and types 65, 65–2 are used to display results diagrams.

3. Results

3.1. Experimental results

The experiment was conducted on the terrace of the Faculty of Mechanical Engineering in Ljubljana, Slovenia for one week from October 14, 2013 to October 21, 2013. The highest solar irradiation during the experiment was on October 17, 2013, which we used for further analysis to compare conventional PV panel and PV-PCM panel. Fig. 6 presents the data for solar irradiation during the October 17, 2013. During the experiment, the temperature of the PV/PCM panel and conventional PV panel were measured. The time step for temperature sampling was 5 min from 9.30 to 15.30. The ambient air temperature increased during the experiment and ranged from 8.5 °C to 18.3 °C. The solar irradiation data takes average solar irradiation in the last 30 min and reached a maximum value of 571 W/m^2 for solar global irradiation and the highest diffuse solar irradiation was 204 W/m^2 at 10:00, due to cloudy weather, which is very common for the city of Ljubljana.

Fig. 7 presents experimental results and comparison of the conventional PV cell temperature, PV-PCM cell temperature and ambient air temperature, measured on October 17, 2013. The PV cells temperature in the conventional PV panel reached maximum 75.5 °C at 13:30, which is 57.7 °C above the ambient air temperature and average temperature of the conventional PV panel during the experiment was 50.3 °C. The temperature of the PV-PCM panel reached maximum 44 °C at the 14:15, which is 26.7 °C above the ambient air temperature and average temperature of the PV-PCM panel during the experiment was 35.9 °C. The maximum difference in the temperature of the PV cells between conventional PV panel and PV-PCM panel was 35.6 °C and average difference in temperature of the PV cells during the experiment was 14.4 °C. As shown in Fig. 7 the temperature of the PV-PCM panel remained at 39–40 °C from 12:30 to 14:00, due to high enough heat flow from PV cells to PCM and therefore the PCM started to change phase from solid to liquid. However, it started to increase in temperature from 2:00 p. m., reaching 44 °C by 14:20. This occurred because the amount of the absorbed solar heat exceeded the required amount of heat for the phase change of the PCM, turning all of it from a solid to a liquid state. At 14:20 when the amount of solar heat gain was reduced, the temperature of the PCM decreased.

Based on the work of E. Radziemska [3] and R. Stropnik [20] the electric power and energy generation efficiency due to PV cell temperature were calculated from experimental results referring to the conventional PV panel. Results shows that the maximum increase of the PV-PCM electric power under the given conditions was 23.2% and average increase of electrical power during the

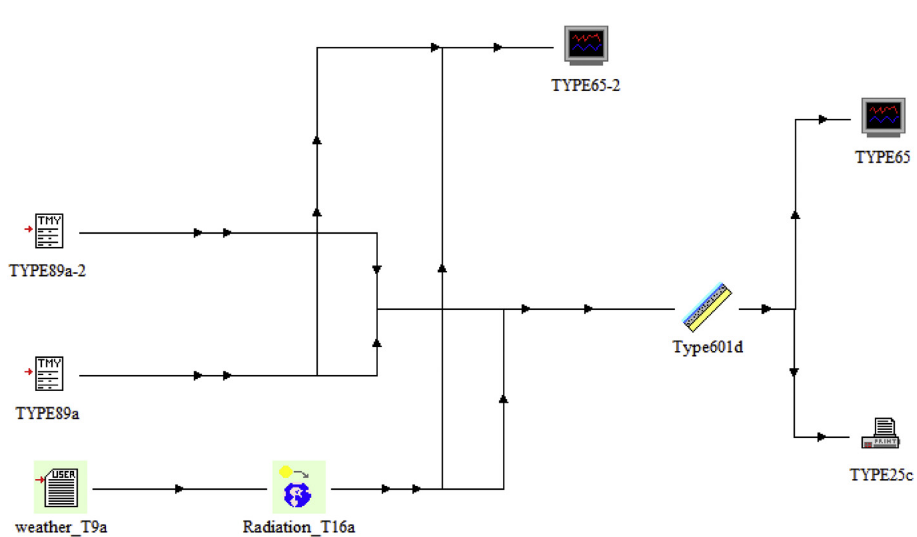

Fig. 5. Configuration of different types for simulation in TRNSYS software.

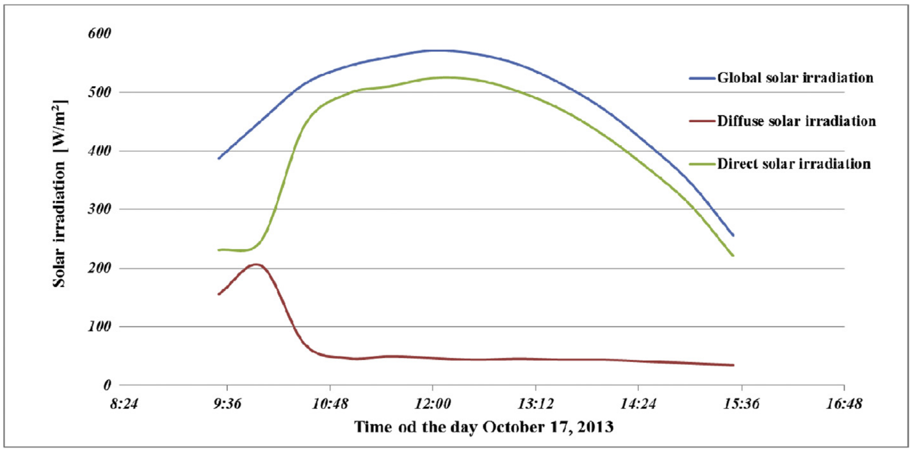

Fig. 6. Solar irradiation during the experiment on October 17, 2013.

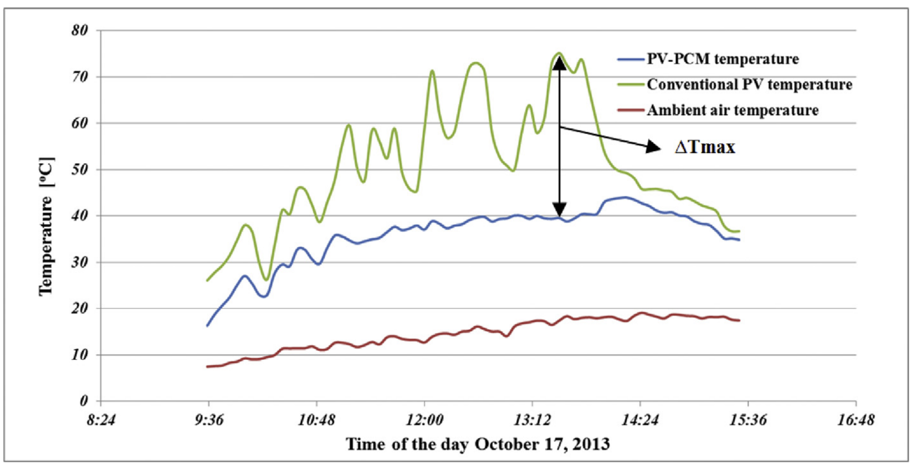

Fig. 7. Temperature of the conventional PV panel, PV-PCM panel and ambient air temperature.

October 17, 2013 was 9.2%. Fig. 8 shows maximum increase of energy generation efficiency of the PV-PCM panel in the given conditions in which was 2.8% and average increase during the experiment was 1.1%.

3.2. Simulation results

3.2.1. Simulation validation

The electric power output and energy generation efficiency of the PV-PCM panel and conventional PV panel were analysed using the methodology above and TRNSYS simulation software, which is widely used by other authors [2,14,21–27]. To verify the use of the simulation methodology to investigate the effect of the PCM on the electric power output and energy generation efficiency of the PV panel, the results of the simulation were compared to those of the actual experiment.

The simulation was conducted under the same conditions used with the experiment on October 17, 2013 and compared with the experimental results of the both measured panels. The results of the temperature of the both panels are presented in Fig. 9. Comparison between simulated and measured average hourly temperature of both PV panels are presented in Table 4, when the solar irradiation was the highest during the October 17, 2013.

The differences between experiment and simulation results in the PV cell temperature were maximum 19.39% for conventional PV panel and 10.63% for PV-PCM panel, due to quick changes of solar energy radiation beam because of partly cloudy weather. Otherwise the simulation nicely follows the measurement results in other times during the maximum solar irradiation where the results showing relatively good correspondence shown in Table 4. For the investigation of the effect of the PCM on the performance of the PV, it was determined that the simulation method has sufficient estimation accuracy in the highest solar irradiation. The greatest effect of the PCM is shown in the time of the day when the solar irradiation reached the highest value and consequently the heat generation in solar cells is bigger.

3.2.2. Electric energy and energy generation efficiency

For analysis how PCM reduces PV cell temperature and increasing the efficiency of PV cells the simulation for the reference year for the city of Ljubljana, Slovenia was made. Based on the methodology for simulation above the computational analysis for annual electric energy and energy generation efficiency was made for conventional and PV-PCM panel with type 601 in TRNSYS software.

The result of annual electric energy and energy generation efficiency are presented in Figs. 10 and 11. The results show that the PV-PCM panel produce more electric energy and have higher electric efficiency than the same conventional PV panel without PCM layer. The highest output was measured during the summer

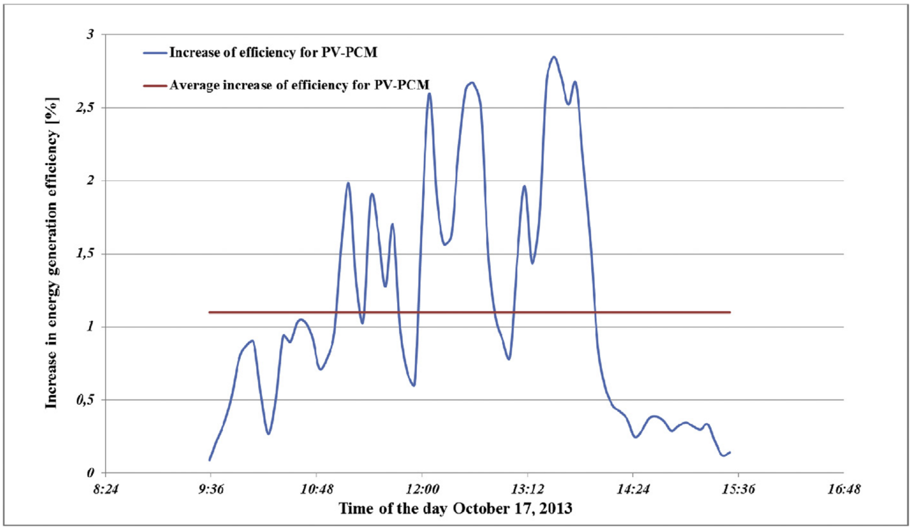

Fig. 8. Increase in energy generation efficiency of PV-PCM panel for given conditions.

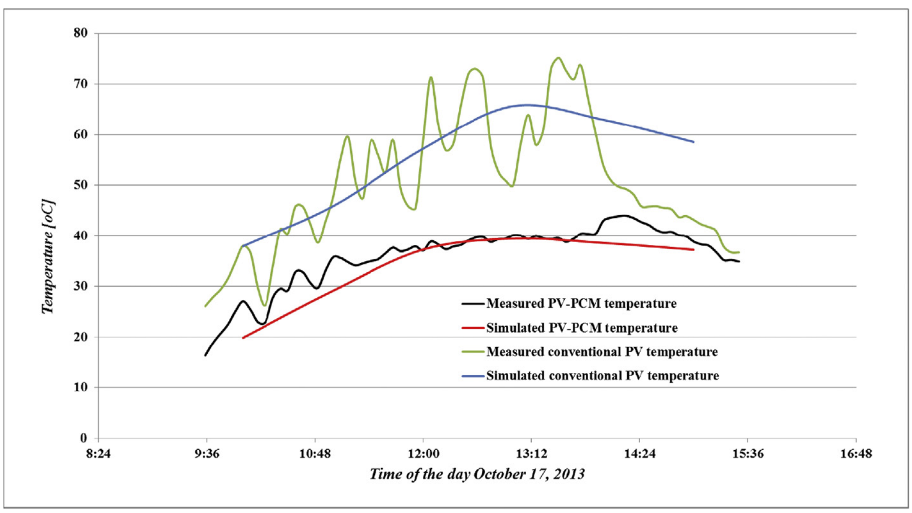

Fig. 9. Simulated and measured temperature of the PV-PCM and conventional PV panel.

Table 4
Comparison of the temperature of the PV-PCM and conventional PV panel.

Time	Average simulated	Average measured	Relative error [%]	Absolute error [°C]
		PV-PCM temperature [°C]		
10.30–11.30	29.13	28.85	0.98	0.28
11.30–12.30	37.26	35.90	3.79	1.36
12.30–13.30	39.43	38.69	1.90	0.74
13.30–14.30	38.55	43.14	10.63	4.59
		Conventional PV temperature [°C]		
10.30–11.30	45.85	38.40	19.39	7.45
11.30–12.30	57.21	52.63	8.70	4.58
12.30–13.30	65.64	62.08	5.73	3.56
13.30–14.30	62.94	65.30	3.62	2.36

months, where the solar radiation is the highest in the year.

Table 5 represents annual results for produced electric energy and energy generation efficiency of PV and PV-PCM panel. Under given weather conditions for the city of Ljubljana the annual electric energy production of PV-PCM panel was 260.17 kWh, which is 17.81 kWh more than conventional PV panel. Increase of electric production of the PV-PCM panel ranges from 4.3 to 8.7% and energy generation efficiency ranges from 0.5 to 1% during the year. Therefore, the annual energy generation efficiency of PV-PCM panel was 0.8% higher than conventional PV panel. With the use of PCM under given conditions the 12.2% energy generation efficiency and 260.17 kWh produced electric energy were achieved, which represents annual increase of 7.3% compared to conventional PV panel.

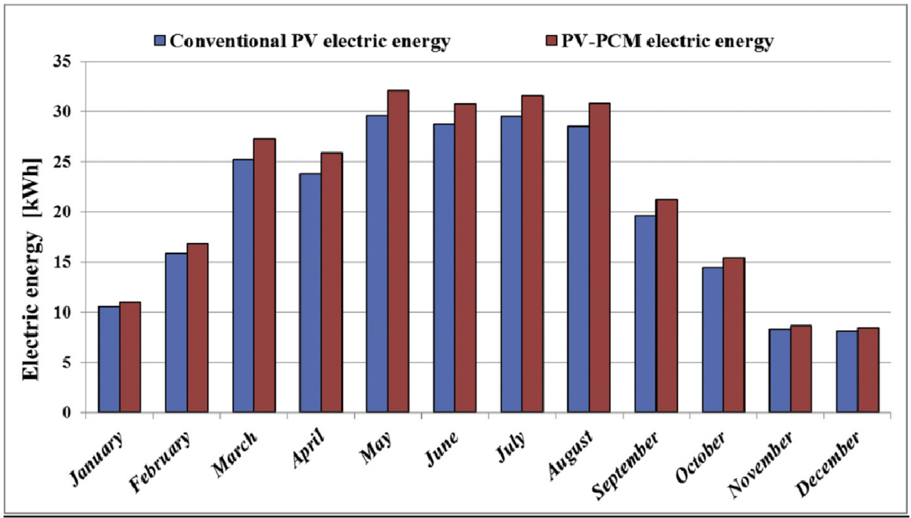

Fig. 10. Produced electric energy of conventional PV and PV-PCM panel during the year.

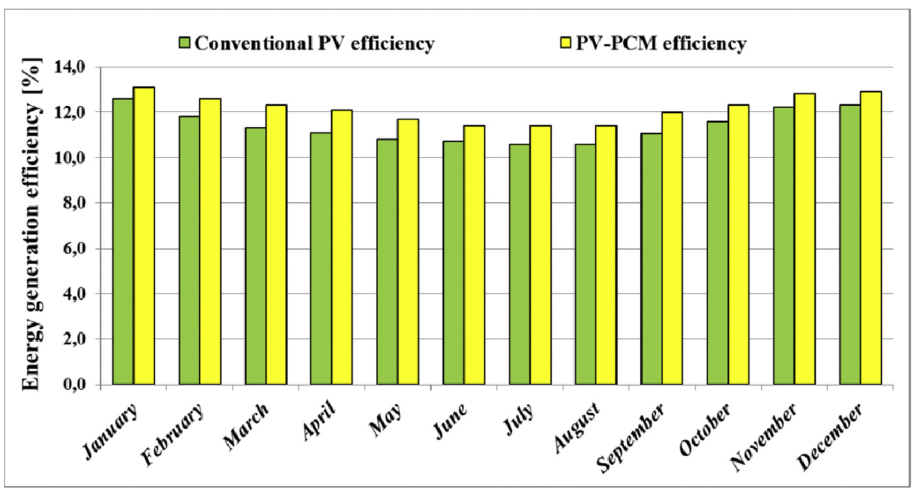

Fig. 11. Energy generation efficiency of conventional PV and PV-PCM panel during the year.

Table 5
Annual electric energy and energy generation efficiency of conventional PV and PV-PCM panel.

Slovenia	Ljubljana	Electric energy [kWh]		Energy generation efficiency [%]		Difference		Increase
Month	Hglob [kWh]	Conventional PV	PV-PCM	Conventional PV	PV-PCM	[kWh]	[%]	[%]
January	52.43	10.58	11.03	12.6	13.1	0.45	0.5	4.3
February	83.37	15.88	16.84	11.8	12.6	0.96	0.8	6.0
March	138.11	25.21	27.25	11.3	12.3	2.04	1.0	8.1
April	133.61	23.82	25.9	11.1	12.1	2.08	1.0	8.7
May	170.04	29.56	32.09	10.8	11.7	2.53	0.9	8.6
June	167.45	28.73	30.77	10.7	11.4	2.04	0.7	7.1
July	173.05	29.5	31.6	10.6	11.4	2.1	0.8	7.1
August	167.81	28.52	30.83	10.6	11.4	2.31	0.8	8.1
September	110.24	19.63	21.23	11.1	12.0	1.6	0.9	8.2
October	77.82	14.49	15.42	11.6	12.3	0.93	0.7	6.4
November	42.45	8.35	8.71	12.2	12.8	0.36	0.6	4.3
December	40.79	8.09	8.47	12.3	12.9	0.38	0.6	4.7
Total	1357.17	242.36	260.17	11.4	12.2	17.81	0.8	7.3

4. Conclusion

In this study, through an experiment the potential for an improvement the electric generation performance of the PV panel with the use of the PCM was analysed under actual outdoor climatic conditions. After validation of the simulation method with experimental results the annual electric energy and energy generation efficiency was simulated for PV-PCM and conventional PV panel with software TRNSYS.

Based on the results of an experiment conducted under outdoor climatic conditions in October 2013, the PV cell temperature of the PV-PCM panel was lower by a maximum of 35.6 °C compared to the conventional PV panel, confirming the effect of a decrease in the temperature by the PCM. Moreover, results show that the average increase of electrical power during the October 17, 2013 was 9.2%. The PV cells temperature of the conventional PV panel reached maximum 75.2 °C, which was 57.7 °C above the ambient air temperature. The PV cell temperature of the PV-PCM panel reached maximum 44 °C, which is 26.7 °C above the ambient air temperature, likewise in other work the average temperature was around 40 °C [28]. An average increase of energy generation efficiency of the PV-PCM panel in the given conditions was 1.1% and maximum was 2.8%. According to the work of other researchers [14,15] the results for energy generation efficiencies and generated energy output are similar.

According to the simulation to analyse the performance improvement of the PV-PCM panel under the given climatic conditions of Ljubljana, Slovenia, the results show that the generated electrical power output increased by 4.3–8.7% and energy generation efficiency increased by 0.5–1%, compared to the conventional PV module. The annual increase for production of electric energy were 7.3% and for energy generation efficiency was 0.8%, compared to the conventional PV panel.

Regarding the intensive R&D efforts of PCM materials and PV panels are expected to improve in the future. For future work another set of experiments for longer period of time and with different geographical locations (hot climates), should be done and compared. Furthermore, enhance PCMs, with different temperature of phase change and non-linear behaviour should be analysed in similar experimental system. Moreover, according to the works done by Refs. [10,13,29] the energy generation efficiency of the PV-PCM module can be improved by increasing the heat transfer between the PCM and the aluminium plate. Therefore, an additional improvement in the energy generation efficiency can be expected with additional fins.

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