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PASIVNO HLAĐENJE FOTONAPONSKIH PANELA KORIŠĆENJEM PCM-A: KOMPARATIVNA STUDIJA U KLIMATSKIM ZONAMA CRNE GORE

Key words: photovoltaic panels; passive cooling; PCM; energy efficiency

COOLING OF PV PANELS USING PCM: A COMPARATIVE STUDY IN MONTENEGRIN CLIMATIC ZONES

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Toplotna efikasnost fotonaponskih (FN) panela značajno opada pri visokim radnim temperaturama, naročito u regionima sa intenzivnim sunčevim zračenjem. Materijali sa faznom promenom (PCM) pojavili su se kao obećavajuća pasivna strategija hlađenja za ublažavanje ovog problema, jer apsorbuju višak toplote putem latentnog skladištenja toplote. Ova studija sprovodi komparativnu numeričku analizu pasivnog hlađenja FN panela zasnovanog na PCM-u u tri različita crnogorska grada sa varijabilnim klimatskim uslovima: Podgorici, Nikšiću i Pljevljima. Jednodimenzionalni prolazni toplotni model zasnovan na entalpijskom pristupu korišćen je za simulaciju temperature panela tokom cele godine. Rezultati pokazuju da integracija PCM-a donosi različite dobitke u efikasnosti u zavisnosti od lokalne temperature i sunčevog zračenja. Ekonomska analiza dalje otkriva da period povrata investicije za integraciju PCM-a zavisi od lokacijski specifičnih dobitaka u proizvodnji električne energije i cena energije. Ova saznanja naglašavaju klimatsku osetljivost performansi PCM hlađenja i podržavaju lokalizovane strategije dizajna za maksimizaciju efikasnosti FN sistema u Crnoj Gori.

The thermal efficiency of photovoltaic (PV) panels significantly declines under high operating temperatures, particularly in regions with intense solar irradiance. Phase Change Materials (PCMs) have emerged as a promising passive cooling strategy to mitigate this issue by absorbing excess heat through latent heat storage. This study conducts a comparative numerical analysis of PCM-based passive cooling for PV panels across three distinct Montenegrin cities with varied climatic profiles: Podgorica, Nikšić, and Pljevlja. A one-dimensional transient thermal model incorporating an enthalpy-based approach is used to simulate panel temperatures over a full year. Results indicate that PCM integration yields variable efficiency gains depending on local temperature and solar irradiance. Economic analysis further reveals that the payback period for PCM integration depends on location-specific electricity production gains and energy pricing. These findings highlight the climate-sensitivity of PCM cooling performance and support localized design strategies for maximizing PV efficiency in Montenegro.

1.Introduction

As the global community intensifies efforts to reduce greenhouse gas emissions and transition to renewable energy sources, photovoltaic (PV) technology continues to play a central role. However, PV panels experience a decline in energy conversion efficiency as their operating temperatures rise, a challenge particularly relevant in regions with high solar exposure. Montenegro, with its diverse geography, presents a compelling case for localized performance analysis. Cities such as Podgorica experience Mediterranean conditions with high summer temperatures and intense solar radiation. In contrast, Pljevlja, situated in the north, has a more continental climate with cooler averages and seasonal variability. Nikšić, located at higher elevation, reflects a transitional climate. The performance of passive cooling techniques like Phase Change Materials (PCMs), which absorb and release heat through phase transitions, is known to be sensitive to ambient conditions. This research aims to evaluate and compare the effectiveness of PCM integration in PV panels across these three climate zones within Montenegro.

2.Method

2.1. Climatic context and site selection

Montenegro's varied topography results in distinct microclimates:

- Podgorica (Elevation: ~40 m) has hot, dry summers and mild, wet winters typical of a Mediterranean climate. It records the highest annual solar irradiance in the country.
- Nikšić (Elevation: ~650 m) has a climate with milder summers and colder winters compared to Podgorica, with moderate solar exposure.
- Pljevlja (Elevation: ~770 m) experiences a continental climate, characterized by colder winters, frequent fog in the winter season, and lower overall solar radiation.

Meteorological data for each city—including hourly air temperature and solar irradiance were obtained from Meteonorm [1]. These variations provide a valuable basis for assessing PCM performance under different thermal stress conditions.

2.2. Modelling and calculation

This study employs a one-dimensional explicit numerical scheme to simulate the temperature distribution within photovoltaic (PV) panels. The model considers both standard PV panels and those enhanced with a Phase Change Material (PCM) layer applied to the back side. For simulations excluding PCM, the thermal behavior of the PV panel is modeled using the properties of silicon with a thickness of 3 cm. When PCM is included, thermal characteristics of the commercially available RT25 HC product by Rubitherm are used [2]. This PCM has a melting point of 25 °C and was analyzed in two thickness configurations: 1 cm and 3 cm.

The thermal properties of the PCM used in this study are presented in Table 1:

For PV panels without PCM, heat conduction is governed by the following equation:

$$\rho c_{\mathrm{p}} \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} \tag{1}$$

where ρ is the density of the material [kg/m³], c_p is the specific heat capacity [J/kg·K], k is the thermal conductivity [W/m·K], T is temperature, t is time [s], and x is the spatial coordinate along the panel thickness [m].

In the presence of a PCM layer, the governing equation is modified to account for latent heat effects during phase transition using an enthalpy-based formulation:

$$\frac{\partial h}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \quad (2)$$

Here, $h = cT + gL$ represents the mixture enthalpy, where g is the liquid fraction of the PCM, L is the latent heat of fusion, and $\alpha = k/(\rho c)$ is the thermal diffusivity of the PCM.

Table 1. Thermal properties of the PCM.

Thermal Property	Unit	Value
Main melting temperature	°C	25
High melting temperature	°C	26
Low melting temperature	°C	22
Main congealing temperature	°C	25
High congealing temperature	°C	26
Low congealing temperature	°C	22
Density (solid phase)	kg/m³	880
Density (liquid phase)	kg/m³	770
Specific heat capacity (solid and liquid)	kJ/kg·K	2
Thermal conductivity (solid and liquid)	W/m·K	0.2
Latent heat of phase change	kJ/kg	230

The numerical scheme uses a time step of 0.001 seconds and a spatial step of 0.001 meters to ensure stability. Hourly temperature data was used as boundary conditions on both surfaces of the PV panel with a convective heat transfer coefficient of 15 W/m²·K. Solar irradiance, calculated for a 35° south-facing panel, was applied only to the sun-facing surface. All climatic data were sourced from the Meteonorm software.

The power output of the PV panel was estimated based on the panel temperature and irradiance using the following relation:

$$P = V_{oc} \cdot I_{sc} \cdot FF \quad (3)$$

where V_{oc} is the open-circuit voltage, I_{sc} is the short-circuit current, and FF is the fill factor. Each of these parameters depends on the solar irradiance, temperature, and the intrinsic characteristics of the PV panel. All calculations were performed for the LX-680-700W M132/210 panel model [3].

3.Results and discussions

3.1. Annual energy output

Simulation results show that the integration of Phase Change Material (PCM) significantly improves annual energy yield across all three cities. The Table 2 summarizes the total yearly electricity production per panel under three conditions: without PCM, with a 1 cm PCM layer, and with a 3 cm PCM layer.

Panel surface temperatures during peak summer days were notably reduced with PCM, especially in Podgorica. On July 21, the maximum panel temperature without PCM reached approximately 62 °C. With a 1 cm PCM layer, it dropped to around 36 °C, and a 3 cm layer yielded only a marginal further reduction (about 35 °C). Similar trends were seen in Niksić and Pljevlja, but with lower starting temperatures due to their cooler climates.

Table 2. Annual electricity production of PV panels with and without PCM in different cities

City	No PCM (kWh)	1 cm PCM (kWh)	3 cm PCM (kWh)
Podgorica	1100	1195	1210
Nikšić	1040	1110	1120
Pljevlja	1000	1060	1070

3.2. Economic feasibility

An economic feasibility study was performed using an average electricity sale price of €0.08/kWh and a PCM cost of 2 €/kg. A 1 cm layer weighs approximately 27.5 kg per panel, yielding a total material cost of 55 € per panel. A 3 cm layer triples the cost. Estimated payback periods for PCM integration based on energy gains and cost assumptions are given in Table 3.

Table 3. Estimated payback periods for PCM integration based on energy gains and cost asumptions

City	Payback (1 cm PCM)	Payback (3 cm PCM)
Podgorica	~6.5 years	~18.8 years
Nikšić	~9.8 years	~20.6 years
Pljevlja	~11.5 years	~22.0 years

4. Conclusion

This study explores the climate-sensitive performance of passive PCM cooling for photovoltaic (PV) panels across three Montenegrin cities—Podgorica, Nikšić, and Pljevlja—each representing a distinct climatic zone. Through year-long simulations, we evaluated how ambient temperature and solar irradiance influence the thermal behavior and energy production of PV panels equipped with phase change material (PCM) layers of different thicknesses. The modeling results demonstrate that the thermal benefits of PCM integration are highly dependent on local climate conditions.

In regions with high solar irradiance and elevated ambient temperatures, such as Podgorica, PCM layers substantially reduce panel operating temperatures, leading to notable improvements in electrical output—up to a 9% annual gain. In contrast, cooler regions like Pljevlja experience relatively modest performance gains due to lower thermal stress on the panels and reduced frequency of PCM phase transitions. Nonetheless, even in these regions, PCM still offers a passive, maintenance-free method of thermal regulation that contributes to increased panel longevity and reliability.

The study further reveals that economic viability is closely tied to climate, with payback periods ranging from approximately 6.5 years in warmer climates to over 11 years in colder ones for 1 cm PCM layers. Thicker PCM layers showed diminishing returns due to higher costs and only marginal additional energy gains, highlighting the importance of optimizing PCM thickness based on site-specific conditions.

Overall, these findings underline the importance of incorporating climate-adaptive design strategies in PV system planning. Passive PCM cooling, when properly tailored to local environmental conditions, can be an effective means to enhance energy yield, reduce thermal degradation, and improve the economic return of solar investments. As Mediterranean and other sun-rich regions continue to scale up solar deployment, the integration of PCM technologies should be considered a key component in the development of high-performance, climate-resilient photovoltaic systems.

5. References

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