A Photovoltaic Panel Integrated with Phase Change Material as Peak Shaving for Domestic Hot Water Energy Demand

Daniele Colarossi¹*, Eleonora Tagliolini¹ and Paolo Principi¹

¹Department of Industrial Engineering and Mathematical Sciences, Università Politecnica Delle Marche, Via Brecce Bianche 12, Ancona, Italy

* corresponding author: d.colarossi@pm.univpm.it

Abstract. Phase change materials (PCMs) applied to photovoltaic (PV) panels are a promising solution to recover the large share of energy from the incident radiation, not converted into electricity. PCMs can store a huge amount of energy, exploiting the solid-liquid phase change, which occurs at a nearly constant temperature. In addition, reducing the temperature of a PV panel increases its electric conversion efficiency. This paper experimentally investigates the match between the heat production of a PV-PCM system and the domestic hot water (DHW) demand of a typical residential building. Different curves of demand are analyzed, all have a peak in the evening period. The solar radiation profile of a typical sunny day is reproduced under a solar simulator. Once the PCM is fully melted, a hydraulic circuit, which connects the heat exchanger immersed in the PCM to a water tank, is activated to extract the heat stored. Different tests are performed by varying the size of the water tank storage. Results show that a storage volume of 50 L, 75 L, 100 L and 125 L ensures a reduction of energy demand of 15.3%, 21.2%, 22% and 21.5% respectively, compared to traditional electric water heaters.

1. Introduction

One of the top priorities in the climate change and global warming challenge is the reduction of the energy consumption in building sector. The main energy demands are heating, cooling and hot water services. Water heating accounts for 14% and 18% of the total residential energy consumption in European Union and United States, respectively [1,2]. The use of renewable energy sources plays a key-role. Nowadays the common solution for domestic hot water (DHW) production is photovoltaics or solar collectors coupled with immersive electric heaters in water tanks [3]. Yildiz et al. [4] conducted an analysis about the possibility to utilize the excess of PV generation in DHW system, covering 48% of the daily demand energy. Knuutinen et al. [5] proposed a solution with photovoltaic (PV) panels connected with a ground source heat pump (GSHP), while Martorana et al. [6] analyzed a photovoltaic thermal system (PVT) to mitigate the interaction with the grid.

A further way to recovery thermal energy and increase the efficiency of a photovoltaic panel is the application of phase change materials (PCMs) [7]. These materials have a large latent heat, which is exploited during the solid-liquid phase change (at a nearly constant temperature) keeping a lower temperature compared to sensible heat storage systems. PCMs suffer from a low thermal conductivity. Solutions have been proposed, as the addition of conductive nanoparticles (graphene) [8], porous media or metallic fins [9], aiming to increase the heat flow rate from the panel to the PCM [10].

This paper presents an innovative solution to cover the evening peak of the DHW demand in a typical residential building. The system consists of a photovoltaic panel integrated with phase change material and coupled with a water storage tank. Previous works focused only on the application of PCM in the water tank (as insulator or inertial mass dipped in water) [12,13]. To maximize the
performance, aluminum fins are glued on the rear surface of the panel and dipped in the PCM, acting as “thermal bridge” for the heat flow. A water circulation system, through a copper heat exchanger, extracts the absorbed heat and stores it in a water tank. The system is experimentally investigated, under a solar simulator. The size of the water tank has been varied. The proposed system aims to provide an additional potential energy saving with a technology already in use, as photovoltaic panels.

2. Materials and method

The tested PV panel is of monocrystalline type, with a nominal power of 40 W and 12 V of voltage. The main characteristics are a module voltage (Vmp) of 17.8 V, a nominal current (Imp) of 2.3 A, a short-circuit current (Isc) of 2.7 A, and an open-circuit voltage (Voc) of 21.3 V. The external dimensions are 64.5 x 50 cm. On the rear surface of the panel, a thin sheet of aluminum was glued and equipped with ten fins to enhance the thermal regulation of the panel. Fins have a length of 52 cm, a height of 2 cm and a thickness of 1 mm.

The phase change material is a paraffin wax, the RT35 HC, produced by the Rubitherm company (Germany). The most important properties are reported in table 1.

| Characteristics          | RT 35 HC                  |
|--------------------------|---------------------------|
| Melting area [°C]        | 34-36 peak 35             |
| Congealing area [°C]     | 36-34 peak 35             |
| Volume expansion [%]     | 12                        |
| Latent heat [kJ/kg]      | 240                       |
| Heat conductivity [W/m² K]| 0.2                       |
| Specific heat capacity [kJ/kg K]| 2                  |
| Liquid/solid density [kg/m³]| 770/880             |

The PCM is contained in a transparent plexiglass box, which allows to monitor the phase change. The box has the same external dimensions of the PV panel (64.5 x 50 cm) with a thickness of 3 cm, while the internal ones are 62.5 cm x 48 cm x 2.5 cm. Inside the box a heat exchanger has been placed, which allows to extract the heat absorbed by the PCM. The heat exchanger consists of 10 parallel copper tubes with an external and internal diameter of 14 mm and 12 mm respectively, and a length of 55 cm. The tubes are welded into two inlet and outlet manifolds, which have a length of 45 cm and an external/internal diameter of 16 mm and 14 mm respectively. In the assembly phase, each fin is immersed in the PCM between two tubes to ensure the maximum heat transfer rate.

The vertical gradient of temperatures in the PCM matrix is provided by four thermocouples. The first one is fixed on the bottom of the plexiglass box, then the others are located at 8 mm from each other, namely 8 mm, 16 mm and 24 mm. The latter coincides with the back face of the PV panel. At a height of 16 mm, two thermocouples are fixed on a copper tube and on a fin, respectively. This provides more accurately data about the heat transfer rate between PCM, fins and tubes. Then two thermocouples measure the temperature of the water at the inlet and outlet of the heat exchanger. Thermocouples are T type (copper-constantan) with a sensitivity of 48.2 μV/°C and a range of measure −200/400 °C. A pyranometer measures the global solar radiation. The model is DPA/ESR 154, with a sensitivity of 10.88 μV/Wm², a linearity of 0.75% and a range of measure from 0 to 2000 W/m². Figure 1 shows the cross section of the PV panel, while figure 2 the overall plant scheme.
Tests were performed under a solar simulator [11]. This allows to maintain the same conditions for the duration of the test. The solar simulator is composed of 20 metal halide lamps. A target area of 2 x 1 meter is uniformly irradiated. In addition, the system is equipped with a vertical guide to adjust the distance between the lamps array and the target area. This way the intensity of the simulated radiation can be progressively reduced.

3. Results and discussions

Tests were performed in laboratories of the Department of Industrial Engineering and Mathematical Sciences of the Polytechnic University of Marche, Ancona, Italy. The solar radiation of a typical day in June has been considered, both theoretically and experimentally (figure 3), and reproduced under the solar simulator. During the charging time, an equivalent radiation of 850 W/m² has been provided. The duration of the equivalent period is calculated to provide the same energy as the theoretical curve. Then during the afternoon, once the extraction system worked, the decrement solar radiation has been simulated in finite steps.

The heat exchanger has been activated at 13:00, when the temperature of the liquid was close to that of the front PV panel (figure 4). At this point, the PCM is no more able to absorb heat from the PV panel and the electrical conversion efficiency of the panel worsens rapidly [9].

Four different water tank sizes have been tested, to investigate the temperature reached while increasing the storage capacity. The sizes are 50L, 75L, 100L and 125 L. The temperature in the tank
has been monitored once the heat extraction system was activated, that is at 13:00 on the typical day considered. The discharge period ended at 18:00, an hour before the peak of the DHW demand of the typical residential building. Figure 5 shows the trend of the water temperature in each test.

![Figure 5](image)

**Figure 5.** Profiles of temperature in the water tank during the discharge time.

At the beginning of the discharge period, the temperature of the water in the tank was around 18.5°C. At the end, the temperature reached in the tank is 25.95°C, 25.35°C, 23.89°C and 22.75°C for the 50L, 75L, 100L and 125L case, respectively.

As regard the heat exchanger, figure 6 shows the temperature difference between the PCM (considering the average of the four temperatures measured in the PCM) and the average temperature of the water between input and output in the heat exchanger. Results are shown for the 4 tests.

![Figure 6](image)

**Figure 6.** Profiles of temperature during the heat extraction period for the 50L (a), 75L (b), 100L (c) and 125L (d) test. The black line indicates the average temperature measured by the thermocouples, while the grey one the average temperature of the water in the heat exchanger.

To evaluate the effectiveness of the heat exchanger the final temperature of the PCM is considered. The average of the four temperatures measured in the PCM has been calculated. A lower final temperature is related to a higher efficiency, as more heat has been released by the PCM and absorbed by the water. Increasing the mass of water in the tank decreases the final temperature of the PCM.

The DHW curves demand were taken from the Regulation (EU) No 814/2013. A list of different profiles is provided depending on the size of the plant. In figure 7 five characteristic profiles are
reported. They all present a peak in the evening period, whose percentage ranges from 45% in profile S to 39.2% in profile M. The energy demand is estimated considering a typical four-person household with a DHW consumption of 200 L/day. The temperature of the inlet water is increased of 30 °C.

The energy saving is calculated as a ratio between the energy stored in the tank at the end of the discharge period and the energy demand (calculated as peak integral) in the evening peak. Results are summarized in table 2.

| Profile | Energy demand [%] | Energy demand [kWh] | Energy saving [%] |
|---------|------------------|--------------------|------------------|
| S       | 45.00%           | 3.13               | 13.43% 19.29% 19.26% 18.77% |
| M       | 36.53%           | 2.54               | 16.54% 23.77% 23.72% 23.12% |
| L       | 37.24%           | 2.59               | 16.23% 23.32% 23.27% 22.68% |
| 3XL     | 38.32%           | 2.67               | 15.77% 22.65% 22.61% 22.04% |
| Average | 39.27%           | 2.73               | 15.39% 22.11% 22.06% 21.51% |

Results show that the best energy saving has been reached with a storage tank of 100L, resulting in a saving of 22.06%. All scenarios have been compared to a fully electric heaters, which heats the inlet cold water from the grid of 30°C. Results range from the 15.39% of the 50L tank to 22.06% of the best solution. The minor yield of the first case is due to the minor capacity of the water. In fact, the final temperature in the tank is the highest one, 25.9°C. This decreases the difference of temperature with the PCM and accordingly the capacity to extract heat. All scenarios turn out to be a good solution to reduce the energy (and environmental) impact of the DHW energy demand in a typical residential building.

4. Conclusions
This paper presents a PV-PCM system as peak shaving for the energy demand peak of domestic hot water in a typical residential building. The system has been experimentally tested. A copper heat exchanger dipped in the PCM discharges the absorbed heat, which is stored in a water tank. Different sizes of the storage (50L, 75L, 100L, 125L) were tested under a solar simulator. An equivalent radiation has been provided during the morning period, to allow the PCM to fully melt. Then the radiation has been decreased in finite steps during the afternoon. Results show that all scenarios ensure an energy saving compared to traditional system (fully electric heaters dipped in water). The building considered is the typical four-person household with a DHW consumption of 200 L/day. All scenarios ensure an energy saving compared to traditional electric water heaters. The percentage of saving ranges from 15.39 (for the storage tank of 50L) to 22.06 (for the 100L case), which turns out to be the best solution. The 75L, 100L, 125L cases return similar results, as they have the minimum storage capacity to store the heat absorbed by the PCM. The maximum temperature in the water tank has been reached for the 50L storage tank, 25.9°C, while the minor one for the 125L case, 22.75°C, as the thermal capacity and the final temperature are inversely proposal. Generally, all proposed scenarios produce a positive effect on the environmental impact of buildings. Further research can be proposed
extending the evaluation all year round, to investigate the seasonal performances. The proposed system can be also applied to other categories of buildings, as offices or other.

5. References

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